Manspeaker & Wand

An Investigation of Bond in Reinforced Concrete Beams

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AN INVESTIGATION OF BOND

IN REINFORCED CONCRETE BEAMS

BY

WELSH WALKER MANSPEAKER
AND
ANTHONY WILLIAM WAND

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This is to certify that the thesis of WELSH WALKER MANSPEAKER and ANTHONY WILLIAM WAND entitled AN INVESTIGATION OF BOND IN REINFORCED CONCRETE BEAMS was prepared under my personal supervision; and I recommend that it be approved as meeting this part of the requirements for the degree of Bachelor of Science in Civil Engineering.

D. A. Abrams

Instructor in Charge.

Recommendation approved:

A N Talbot

Professor of Municipal and Sanitary Engineering in Charge of Theoretical and Applied Mechanics.

Recommendation approved:

Ira O. Baker.

Professor of Civil Engineering.

TABLE OF CONTENTS

INDEX TO

TABLES AND FIGURES

Tables

Figures

I. INTRODUCTION.

1. Purpose of Thesis.—The purpose of this thesis is to give further information on the bond between concrete and steel in reinforced concrete beams, and to compare the bond stresses developed in beams with those of pull-out specimens made from the same materials. With this object in view a series of tests was conducted on concrete beams reinforced with horizontal bars. The web reinforcement of the beams consisted of V-shaped vertical stirrups. All beams were 8 in. wide and 12 in. total depth; depth to center of steel 10 ins. The span length was generally 6 ft.; a few of the beams had span lengths of 5, 7, 8, and 10 ft.

A series of tests were made upon pull-out specimens for the purpose of making a comparison of the bond stresses developed in the pull-out specimens and the beams.

A number of tests were made upon the beams for the purpose of giving information on the slip of the bar, at various points in the beam under the load.

2. Scope of the Work.—The test specimens consisted of 75 beams designed to develop high bond stress, of different lengths, reinforced with plain and deformed bars, varying in size from 5/8-in. to 1 1/8 in. in diameter. The beams were tested with the loads applied at different distances apart to determine what effect this had on the bond between the concrete and steel. The effect of long-continued load was studied from two tests on 10-ft. beams.

The beam was loaded until a slip of the bar at the ends occurred, and then allowed to remain under this load, the purpose being to determine if this load would cause the beam to fail by bond.

The compressive stress of the concrete was determined by testing 129 6-in. cubes. 183 pull-out specimens were tested, reinforced and made of the same concrete as the beams.

II. MATERIALS, TEST PIECES, AND METHOD OF TESTING.

3. Cement and Aggregates.—The cement used was furnished by the Universal Portland Cement Company. Tests of this cement are given in Table 1.

The sand used was torpedo sand from near Attica, Indiana. It was of a good quality, fairly sharp, clean and well graded. The mechanical analysis from five samples of this sand is given in Table 2.

A good quality of rather hard limestone from Kankakee, Illinois, was used. It is representative of the stone used in the experimental work of the Engineering Experiment Station. The average mechanical tests of five samples are given in Table 3.

4. Concrete.—All specimens were made of 1-2-4 concrete. The concrete was proportioned by loose volume, considering 1 cubic foot of cement to weigh 95 lb. The materials were weighed also in order to secure a check on the proportioning. Table 4 gives the proportions of the materials by weight in the different batches from which the beams and auxiliary specimens were made.

Men skilled in mixing concrete and making test pieces were employed in the work. The concrete for the first 27 beams (corresponding to the first beam made in each set of three) was mixed by hand with shovels. The sand and cement were first mixed dry; the stone, which had previously been thoroughly moistened, was added and the mix then turned until of a uniform appearance. Usually the first operation included about five turnings and the

second not less than three. Water was added in a sufficient quantity to give a fairly wet mixture. The whole was then turned until thoroughly mixed. The concrete for the remainder of the specimens was machine-mixed. The machine was a 9 cu-ft. batch mixer, manufactured by the Marsh-Capron Company, Chicago, Illinois. The mixer drum turned about 22 times per minute. It was operated by an electric motor. With the machine running continuously the stone and sand were placed in the mixer and about one-half the required amount of water admitted. The cement was then added and the remainder of the water admitted as quickly as possible. The batch was mixed for about 5 minutes after adding the cement. The practice of mixing the cement and aggregate dry before admitting the water was discontinued as it was found that there was a tendency for the dry material to "cake" in and around the elevating scoops and deflecting blades and remain in the mixer when the batch was discharged. By mixing the materials wet the mixer would discharge nearly all of the materials put in.

When mixing was complete, the batch was discharged onto the concrete floor from whence it was removed to the forms by means of shovels or in a wheel-barrow.

5. Steel.—The steel reinforcing bars consisted of plain round bars 5/8 to 1 in. in diameter; 1-in. square bars, 1-in. square bars twisted, one twist per foot, 1 1/8-in. corrugated round bars, and 1-in. plain round bars threaded at the ends. Tensile tests of the steel were not made, as it was not expected that the steel stresses would be excessive. All bars except the 1 1/8-in. corrugated rounds were of mild steel; the corrugated bars were of high carbon steel.

TABLE 1.

BRIQUETTE TESTS OF UNIVERSAL PORTLAND CEMENT.

Each value is the average from five tests.

Loads are given in pounds per square inch.

Sample No.	Date	Neat Cement 7 Days	Neat Cement 28 Days	1 – 3 Mortar 7 Days	1 – 3 Mortar 28 Days
1	Oct. 25, 1911	585	685	239	315
2	Nov. 11, 1911	577	694	225	297
3	Dec. 7, 1911	691	715	242	306
4	Dec. 22, 1911	617	792	231	326
5	Jan. 10, 1912	588	672	246	333
6	Feb. 12, 1912	612	758	253	323
7	Feb. 28, 1912	698	884	287	372
Average		624	743	246	325

Additional tests on this cement showed the initial set to occur at 3 hr. 5 min. and final set at 6 hr. 32 min. after mixing. Sieve tests showed 97.2% passing a No. 100 sieve and 81.8% passing a No. 200 sieve.

The cement tests were made according to standard methods by Mr. B. L. Bowling at the Cement Testing Laboratory, University of Illinois.

TABLE 2.

MECHANICAL ANALYSIS OF SAND.

Average of five samples.

Sieve No.	Separation Size inches	Per cent Passing
3	0.28	100.0
5	.174	88.0
10	.091	54.3
12	.067	47.5
16	——	41.7
18	.043	32.9
30	.027	21.2
40	.019	13.3
50	.013	5.1
74	.009	2.7
150		1.0

TABLE 3.

MECHANICAL ANALYSIS OF STONE.

Average of five samples.

Size of Square Opening	Separation Size inches	Per cent Passing
1 in.	——	100.0
3/4 in.	——	95.5
1/2 in.	——	66.7
3/8 in.	——	46.3
No. 3	0.28	25.9
No. 5	.174	8.1
No. 10	.091	3.4

6. Test Beams.—All of the beams herein described, were 8 in. wide and 12 in. deep, the center of the longitudinal reinforcement being placed 10 in. below the top surface of the beam. The longitudinal reinforcement generally consisted of a single bar. In one set of 3 beams 4 5/8-in. rounds were used, and in one set 3 3/4-in. rounds were used. The span length was generally 6 ft. In a few of the tests the span length of the beam varied from 5 to 10 ft. The total length of the beams in each case was made 6 in. greater than the span length. All beams were reinforced with stirrups of 1/2-in. rounds placed vertically 6 in. apart. In all beams reinforced with a single longitudinal bar, the stirrups were V-shaped, with ends bent inward, and passed under the longitudinal bar. U-shaped stirrups were used in the beams reinforced with 5/8- and 3/4-in. rounds. These stirrups were left projecting about 1/2-in. above the top surface of the beam.

7. Making Test Beams.—Generally enough concrete was mixed in one batch to make two beams and the corresponding auxiliary specimens. The beams and auxiliary test specimens were made between Nov. 1, 1911 and Jan. 29, 1912. One beam from each set of three was made before beginning on the second set; thus the making of the beams in any set was distributed over the season and accidental variation may not be expected to affect one set more than another. The first beam of each set was made of hand-mixed concrete; all others were machine-mixed. The beams were made directly on the concrete floor of the laboratory, with a strip of building paper beneath the forms. The forms consisted of the ordinary collapsible wooden forms held together by clamps. Enough concrete was placed

in the form to fill it a little above the desired level of the center of the reinforcement. The reinforcement was then placed and properly adjusted by tamping it down to grade. The forms were then filled in layers of about 4 in. After each layer had been tamped the concrete was spaded back from the form in order to produce a better surface and to make sure that the corners of the form were well filled, the layer was then retamped a second time. The forms were removed after 7 days, but the beams were not removed from their place on the floor until a few days before the date of the test. Table 4 gives detailed information concerning the dimensions of all the beams and materials used in each batch. This table also contains the average values for the compressive tests of the 6-in. concrete cubes. Each value is the average of three tests.

8. Minor Test Pieces.—From each batch of concrete one or more sets of three pull-out specimens, and three 6-in. cubes were made. The pull-out specimens consisted of a steel rod similar to that used in the corresponding beam, embedded in the center of a concrete cylinder 8 in. in diameter and 8 in. long. Thus the depth of embedment of the bar was 8 in. in all cases. The specimens were made in a vertical position with the bar projecting about 1/4-in. above and about 16 in. below the cylinder. The 6-in. cubes were made in sets of three. The cubes and pull-out specimens were made in metal forms.

9. Storage of Test Specimens.—The beams remained on the floor of the mixing room until a few days before the date of test, when they were removed to the Testing Laboratory. During the time

TABLE 4.

DATA OF REINFORCED CONCRETE BEAMS.

1-2-4 concrete, proportioned by loose volume. The concrete for the first beam of each set was mixed by hand, all other was machine-mixed.
All beams were 8 in. wide, depth to center of steel 10 in. total depth 12 in.

Beam No.	Length ft. in.	Reinforcement: Size and kind of bars	Reinforcement: Per cent Steel	Beam From Same Batch	Mixture by Weight	Compression Tests of 6-in. cubes: Age Days	Compression Tests of 6-in. cubes: Av. of 3 tests lb. per sq. in.
1052.1	6'-6"	1-in. plain round	0.98	1051.1	1-1.95-3.34	70	2120
.2	do.	do.	0.98	———	1-1.95-3.34	61	2730
.3	do.	do.	0.98	———	1-1.93-3.23		
1052.4	6'-6"	do. 4 3/8-in. auxiliary bars at ends.	0.98	1055.1	1-2.07-3.48	61	2065
.5	do.		0.98	———	1-1.92-3.20	66	2640
.6	do.	do.	0.98	1058.3	1-1.93-3.32	60	2960
1056.1	6'-6"	1-in. plain round	0.98	1057.1 1058.1	1-1.94-3.29	62	2140
.2	do.	do.	0.98	———	1-2.00-3.20	68	3500
.3	do.	do.	0.98	———	1-2.00-3.36		
1057.1	6'-6"	do.	0.98	1056.1 1058.1	1-1.94-3.29	62	2140
.2	do.	do.	0.98	———	1-1.98-3.34		
.3	do.	do.	0.98	———	1-1.93-3.23		
1058.1	6'-6"	do.	0.98	1056.1 1057.1	1-1.94-3.29	62	2140
.2	do.	do.	0.98	———	1-1.96-3.27	66	2730
.3	do.	do.	0.98	1052.6	1-1.93-3.32	60	2960
1059.1	6'-6"	do.	0.98	1061.1 1048.1	1-2.07-3.46	60	2680
.2	do.	do.	0.98	———	1-1.99-3.32	66	2600
.3	do.	do.	0.98	———	1-1.92-3.31	67	2600
1060.1	6'-6"	do.	0.98	1059.1 1048.1	1-2.07-3.46	60	2680
.2	do.	do.	0.98	———	1-2.01-3.23	64	3140
.3	do.	do.	0.98	1063.3 1064.3	1-1.98-3.30	63	3250
1050.1	6'-6"	3, 3/4-in. plain round	1.66	1055.7	1-2.01-3.32	60	2220
.2	do.	do.	1.66	———	1-2.02-3.29	66	3290
.3	do.	do.	1.66	———	1-1.95-3.36		

TABLE 4 (Cont.).

Beam No.	Length ft. in.	Reinforcement: Size and kind of bars	Reinforcement: Per cent Steel	Beam From Same Batch	Mixture by Weight	Compression Tests of 6-in. cubes: Age Days	Compression Tests of 6-in. cubes: Av. of 3 tests lb. per sq. in.
1050.4	6'-6"	4, 5/8-in. plain round	1.53	1053.1	1-1.95-3.09	60	2170
.5	do.	do.	1.53	—	1-2.02-3.14	62	2700
.6	do.	do.	1.53	1061.3	1-1.95-3.32	60	2390
1051.1	5'-6"	1-in. plain rounds	0.98	1052.1	1-1.95-3.34	70	2120
.2	do.	do.	0.98	—	1-1.94-3.23	66	2800
.3	do.	do.	0.98	—	1-1.98-3.28	68	2760
1046.1	6'-6"	1-in. square bars	1.25	1054.1	1-1.93-3.26	62	2580
.2	do.	(side horizontal)	1.25	—	1-1.91-3.20	68	3790
.3	do.	do.	1.25	—	1-1.93-3.25	59	2800
1046.4	6'-6"	1-in. square bars	1.25	1047.1	1-1.96-3.29	60	2190
.5	do.	(placed on edge)	1.25	—	1-1.96-3.35	68	1890
.6	do.	do.	1.25	—	1-1.98-3.39	64	2080
1047.1	6'-6"	1-in. sq. twisted bars	1.25	1046.4	1-1.96-3.29	60	2190
.2	do.	(1 twist per ft.)	1.25	—	1-1.98-3.34	71	2980
.3	do.	do.	1.25	—	1-1.95-3.36	59	2670
1048.1	6'-6"	1-1/8-in. corr. round	1.24	1059.1 1060.1	1-2.07-3.46	60	2680
.2	do.	4 stirrups at each end	1.24	—	1-1.96-3.24	61	3150
.3	do.	do.	1.24	—	1-1.91-3.30		
1048.4	6'-6"	do.	1.24	1055.4	1-2.03-3.28	61	1940
.5	do.	do.	1.24	—	1-2.05-3.19	65	3260
.6	do.	do.	1.24	—	1-1.98-3.34		
1061.1	6'-6"	1-in. round threaded	0.98	1062.1	1-2.06-3.56	64	1570
.2	do.	27-in. at each end	0.98	—	1-1.94-3.19	67	3130
.3	do.	do.	0.98	1050.6	1-1.96-3.31	60	2390
1061.4	6'-6"	1-in. round threaded	0.98	1063.1 1064.1	1-2.07-3.52	63	2240
.5	do.	27-in. at each end	0.98	—	1-1.98-3.25	64	2760
.6	do.	(rod polished)	0.98	1054.3	1-1.98-3.30	63	2870
1062.1	6'-6"	1-in. round threaded	0.98	1061.1	1-2.06-3.56	64	1570
.2	do.	21-in at each end	0.98	—	1-2.02-2.82		
.3	do.	do.	0.98	—	1-1.93-3.28		
1063.1	6'-6"	1-in. round threaded	0.98	1061.4 1064.1	1-2.07-3.52	63	2240

TABLE 4 (Cont.).

Beam No.	Length ft. in.	Reinforcement: Size and kind of bars	Reinforcement: Per cent Steel	Beam From Same Batch	Mixture by Weight	Compression Tests of 6-in. cubes: Age Days	Compression Tests of 6-in. cubes: Av. of 3 tests lb.per sq. in.
1063.2	6'-6"	15-in. at each end	0.98	——— 1060.3	1-1.99-3.21	62	2070
.3	do.	do.	0.98	1064.3	1-1.98-3.30	63	3250
1064.1	6'-6"	1-in. round threaded	0.98	1061.4	1-2.07-3.52	63	2240
.2	do.	9-in. at each end	0.98	1063.1 ——— 1060.3	1-1.97-3.24		
.3	do.	do.	0.98	1063.3	1-1.99-3.26	63	3250
1053.1	7'-6"	1-in. plain rounds	0.98	1050.4	1-1.95-3.09	60	2170
.2	do.	do.	0.98	———	1-1.98-3.15	62	2200
.3	do.	do.	0.98	———	1-1.98-3.29		
1054.1	8'-6"	1-in. plain rounds	0.98	1046.1	1-1.93-3.26	62	2580
.2	do.	do.	0.98	———	1-1.96-3.28	65	2800
.3	do.	do.	0.98	1061.6	1-1.98-3.30	63	2870
1055.1	10'-6"	1-in. plain rounds	0.98	1052.4	1-2.07-3.48	61	2065
.2	do.	do.	0.98	———	1-1.99-3.28		
.3*	do.	do.	0.98	———	1-1.98-3.37		
1055.4	10'-6"	1-in. plain rounds	0.98	1048.4	1-2.03-3.28	61	1940
.5	do.	do.	0.98	———	1-2.05-3.13		
.6*	do.	do.	0.98	———	1-1.97-3.27		
1055.7	10'-6"	1-in. plain rounds	0.98	1050.1	1-2.01-3.32	60	2220
.8	do.	do.	0.98	———	1-2.05-3.44	65	2980
.9	do.	do.	0.98	———	1-1.99-3.31	67	2870
1049.1	10'-6"	1-1/8 in. corr. round	1.24	———	1-1.97-3.28	63	2420
.2	do.	do.	1.24	———	1-2.01-3.19	62	2440
.3*	do.	do.	1.24	———	1-1.95-3.32		

*Not tested in time for this report.

The average compressive strength of 36 6-in. cubes of hand-mixed concrete is 2200 lb. per sq. in.; of 93 cubes of machine-mixed concrete, 2800 lb. per sq. in.

of storage they were wet with water from a hose once each day.

The pull-out specimens were stored with the beams; the 6-in. cubes were covered with damp sand as soon as the forms were removed, and remained in the sand until the time of test.

10. Method of Testing Beams.—In testing, the beams were loaded at the third points except in four sets of beams as indicated in Table 5, in which the load was applied at two points nearer the supports. The beams were all tested in a 200 000-lb. Olsen testing machine. The load was transmitted to the beams by means of an I-beam resting on turned steel rollers. The beams rested on rocker pedestals. A rubber cushion was placed between the concrete and bearing plates at both load points and supports.

The center deflection of each beam was measured with an Ames extensometer. The instrument was carried by a wooden bar which was clamped to the beam over the supports. The plunger of the instrument made contact with a small metal bracket attached to the middle of one side of the beam at mid-depth by means of plaster of paris. The slip of the ends of the bar and at other points was measured with Ames extensometers. The instruments were fastened to the ends of the beam by means of metal clamps. The plunger of the instrument was placed against the end of the bar, thus any slip of the bar caused the pointer to move over a graduated dial. This instrument is graduated to read directly to 0.001 in., but readings were estimated to the nearest 0.0002 in. The loads were applied in increments of 1000 or 2000 lbs. After applying an increment of load the machine was stopped while readings of center deflection, and the other instruments were taken, and the cracks in the beam mapped in

TABLE 5.

TESTS OF REINFORCED CONCRETE BEAMS.

Loads are given in pounds; stresses are given in pounds per square inch.
In computing unit stresses the weight of the beam has been considered.
All beams had 3 in. overhang at each end.

Beam No.	Age Days	Test Span ft.	Distance Between Loads ft.	Load at First Diag. Crack	At First Slip of End of Bar: Load	At First Slip of End of Bar: Bond Unit Stress	At Maximum: Applied Load	At Maximum: Stress in Steel	At Maximum: Vertical Shear	At Maximum: Bond Unit Stress	Failure
1052.1	67	6	2	8 000	8 000	160	19 940	36 800	151	383	Bond bar pulled out at S. end
.2	59	6	2	8 000	10 000	198	18 000	33 200	137	347	" " " " " N. "
.3	64	6	2	6 000	12 000	235	20 000	36 800	152	385	Tension in steel
1052.4	61	6	2	8 000	17 000	328	20 600	37 900	170	395	Bond at N. end
.5	63	6	2	10 000	10 000	198	18 500	34 100	140	356	Tension in steel
.6	65	6	2	14 000	14 000	273	18 800	34 700	143	363	" " "
1056.1	65	6	2	12 000	12 000	235	15 750	29 200	120	305	Bond at N. end
.2	65	6	2	8 000	12 000	235	19 700	36 300	149	379	Bond and tension in steel
.3	65	6	2	8 000	12 000	235	21 000	38 600	159	403	Bond at N. end
1057.1	68	6	2½	8 000	10 000	198	19 500	31 400	148	375	Bond and diagonal tension
.2	64	6	2½	8 000	12 000	235	19 100	30 800	146	368	Bond and diagonal tension
.3	63	6	2½	8 000	12 000	235	25 000	40 000	189	478	Bond at N. end
1058.1	68	6	3	8 000	12 000	235	18 900	26 100	143	364	Bond at N. end
.2	63	6	3	6 000	10 000	198	14 000	19 500	108	272	Bond at both ends
.3	67	6	3	— —	8 000	160	18 600	25 700	141	359	Bond at N. end
1059.1	64	6	3½	10 000	12 000	235	29 000	33 100	218	552	Tension in steel
.2	59	6	3½	6 000	8 000	160	17 700	18 200	135	341	Bond at S. end
.3	62	6	3½	12 000	10 000	198	22 000	25 200	166	421	Bond at N. end
1060.1	70	6	4	21 000	12 000	235	32 000	29 100	240	608	Bond at S. end
.2	62	6	4	12 000	16 000	309	24 700	22 600	186	472	Bond at N. end
.3	61	6	4	12 000	16 000	310	30 000	27 300	225	573	" " " "
1050.1	61	6	2	12 000	20 000	183	34 500	38 600	267	308	Bond and diagonal tension
.2	62	6	2	12 000	18 000	166	26 000	29 200	203	235	" " " "
.3	57	6	2	10 000	18 000	166	31 200	34 900	243	279	Tension in steel
1050.4	60	6	2	10 000	14 000	118	33 700	40 200	259	269	Bond and diagonal tension
.5	62	6	2	8 000	14 000	118	34 000	40 700	261	271	Tension in steel
.6	60	6	2	6 000	16 000	134	27 900	33 300	215	225	Bond at N. end
1051.1	68	5	1⅔	8 000	15 000	290	16 800	25 800	128	324	Bond at S. end
.2	60	5	1⅔	6 000	8 000	159	20 000	30 600	151	383	Bond at N. end
.3	63	5	1⅔	8 000	14 000	271	20 100	30 800	152	385	Bond and diagonal tension

TABLE 5. Continued

Beam No.	Age Days	Test Span ft.	Distance Between Loads ft.	Load at First Diag. Crack	At First Slip of End of Bar: Load	At First Slip of End of Bar: Bond Unit Stress	At Maximum: Applied Load	At Maximum: Stress in Steel	At Maximum: Vertical Shear	At Maximum: Bond Unit Stress	Failure
1046.1	62	6	2		10 000	160	19 000	27 800	146	293	Bond at S. end
.2	62	6	2	10 000	10 000	160	19 300	28 200	148	298	Bond at N. end
.3	57	6	2	10 000	11 000	175	20 500	30 000	157	316	Bond and diagonal tension
1046.4	61	6	2	8 000	10 000	160	20 000	29 200	154	308	Bond and diagonal tension
.5	62	6	2	8 000	8 000	129	12 000	17 800	94	188	Bond at N. end
.6	64	6	2	10 000	12 000	189	16 700	24 500	129	263	" " N. "
1047.1	62	6	2	9 000	10 000	160	21 800	31 800	167	335	Bond at N. end
.2	65	6	2	6 000	10 000	160	23 400	34 100	179	359	" " N. "
.3	60	6	2	6 000	10 000	160	20 600	30 100	158	317	" " N. "
1048.1	70	6	2	13 000	14 000	246	31 550	46 000	239	541	Bond and diagonal tension
.2	59	6	2	11 000	10 000	179	27 600	40 300	209	475	Bond at N. end
.3	60	6	2	8 000	16 000	280	28 300	41 300	215	486	Bond at S. end
1048.4	62	6	2	8 000	8 000	146	25 000	36 600	191	431	Tension in steel
.5	63	6	2	8 000	10 000	179	27 700	40 500	211	477	Bond and diagonal tension
.6	64	6	2	8 000	14 000	246	25 000	36 600	191	431	Bond at N. end
1061.1	63	6	2	4 000	6 000	136	18 000	41 700	137	387	Diagonal tension
.2	61	6	2	8 000	10 000	220	18 000	41 700	137	387	Tension in steel
.3	65	6	2	6 000	14 000	304	19 600	45 500	148	421	" " "
1061.4	63	6	2	8 000	(No slip)		19 000	44 100	144	409	Tension in steel
.5	64	6	2	8 000	11 000	241	17 800	41 400	135	383	" " "
.6	65	6	2	6 000	11 000	241	17 000	39 600	129	367	" " "
1062.1	63	6	2	6 000	10 000	220	19 900	46 100	150	428	Tension in steel
.2	62	6	2	6 000	9 000	199	17 800	41 400	185	384	Bond at N. end
.3	62	6	2	6 000	10 000	220	21 000	48 600	159	450	Tension in steel
1063.1	63	6	2	8 000	11 000	241	21 900	50 600	166	469	Tension in steel
.2	62	6	2	8 000	12 000	262	20 500	47 500	155	440	" " "
.3	60	6	2	8 000	8 000	178	19 500	45 200	148	419	" " "
1064.1	64	6	2	8 000	10 000	220	21 000	48 600	159	450	Tension in steel
.2	65	6	2	6 000	10 000	220	19 000	44 100	144	410	" " "
.3	61	6	2	10 000	10 000	220	20 300	47 000	154	436	" " "
1053.1	62	7	$2\frac{1}{3}$	8 000	(No reading)		17 100	37 000	130	331	Tension in steel
.2	63	7	$2\frac{1}{3}$	8 000	11 000	217	16 600	36 000	126	322	Bond and tension in steel
.3	63	7	$2\frac{1}{3}$	8 000	14 000	273	18 400	39 800	139	356	Tension in steel

TABLE 5. Continued

Beam No.	Age Days	Test Span ft.	Distance Between Loads ft.	Load at First Diag. Crack	At First Slip of End of Bar		At Maximum				Failure
					Load	Bond Unit Stress	Applied Load	Stress in Steel	Vertical Shear	Bond Unit Stress	
1054.1	60	8	$2\frac{2}{3}$		8 000	163	16 000	40 000	124	312	Tension in steel
.2	63	8	$2\frac{2}{3}$	5 000	6 000	126	15 100	37 800	117	296	" " "
.3	60	8	$2\frac{2}{3}$	8 000	12 000	237	15 400	38 500	120	301	" " "
1055.1	64	10	$3\frac{1}{3}$	4 500	(No slip)		12 300	39 800	106	245	Tension in steel
.2	60	10	$3\frac{1}{3}$	4 000	10 000	203	12 300	39 800	106	246	" " "
1055.4	64	10	$3\frac{1}{3}$	4 000	7 000	146	10 800	35 300	89	218	Tension in steel
.5	65	10	$3\frac{1}{3}$	4 000	8 000	165	9 900	32 600	83	201	" " "
1055.7	62	10	$3\frac{1}{3}$	4 000	12 100	242	12 100	39 200	99	242	Tension in steel
.8*	93	10	6	4 000	10 000	203					
.9	85	10	6	4 000	12 000	240	16 000	30 500	127	315	Bond at S. end
1049.1	61	10	$3\frac{1}{3}$	6 000	14 000	251	21 000	52 500	166	369	Tension in steel
.2	63	10	$3\frac{1}{3}$	8 000	14 000	251	21 100	52 700	168	371	" " "

* Test not completed.

the note book and on the beam the load was marked at the end of the crack.

The slip of the bar was measured also at points other than at the ends. Table 6 gives a list of some of these beams tested in this manner. In the bottom of the beam holes were cut through the concrete to the steel. A hole was drilled in the longitudinal reinforcing bar and a threaded 1/2-in. square steel plug inserted. The instruments fastened to a metal bracket were then attached to the concrete by means of plaster of paris, in such a manner that the plunger rested against the steel plug. Thus slip of the bar in either direction was indicated. The bracket was of such shape that the instrument was supported by the concrete in the same vertical plane as the steel plug with which it made contact. This may be considered as equivalent to measuring the deformation over a zero gauge length. From four to ten instruments were attached to the bottom of the beams which were tested in this way. They were generally placed in pairs symmetrical with respect to the center line as shown in photograph Fig. 1. A sample log sheet of a test of this kind is shown in Table 7.

11. Method of Testing Pull-out Specimens.—The pull-out specimens were tested on a 100 000-lb. Riehle machine. The rate of movement of the pulling head was 0.05-in. per minute. In testing, the specimens were placed over the weighing head of the machine. The lower end of the embedded bar was held in the grips of the pulling head, the load being transmitted from the concrete cylinder to the cast-iron base plate, on a flat rubber cushion, to a spherical bearing block through which it passed to the weighing head of the

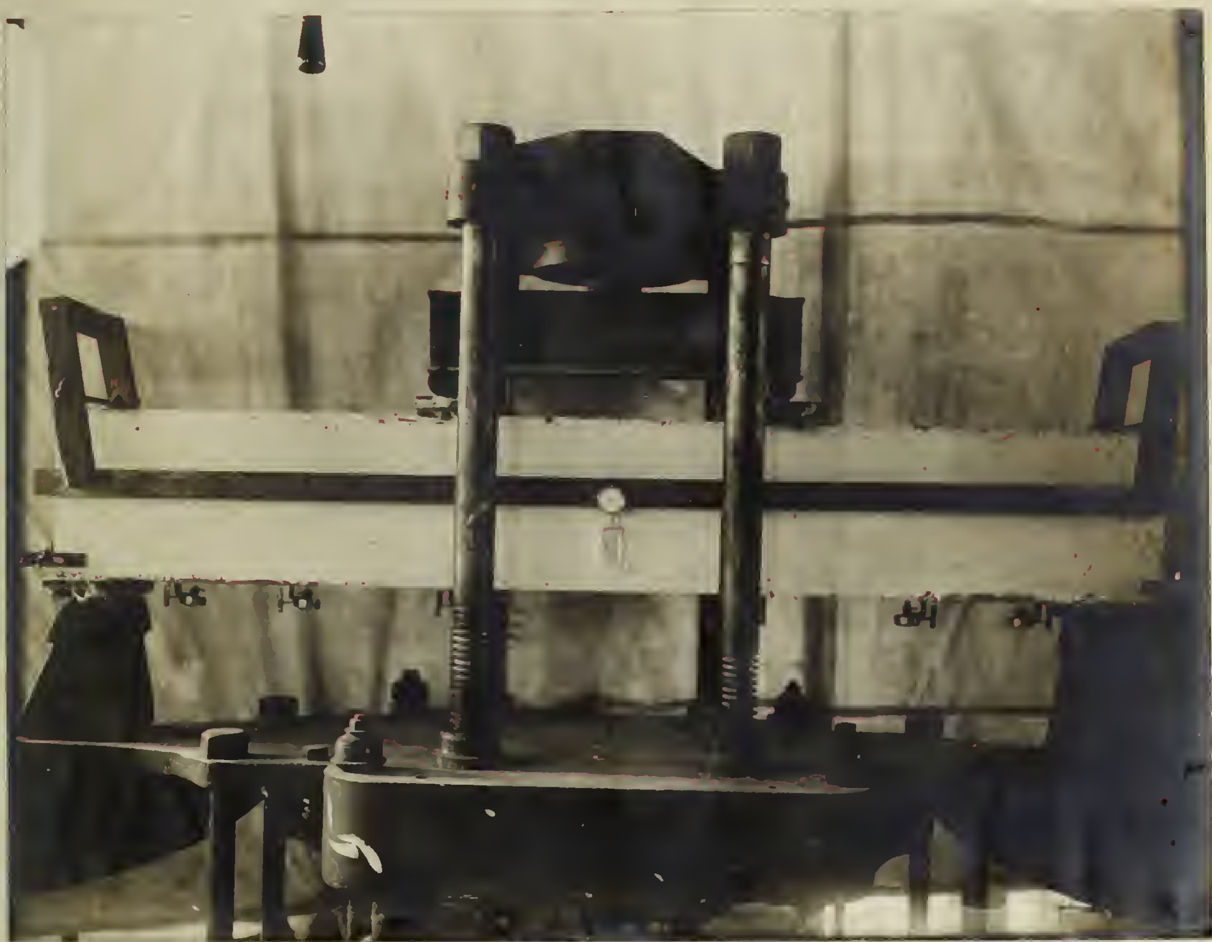


FIG. 1.

VIEW OF BEAM IN TESTING MACHINE
AND ATTACHMENT OF INSTRUMENTS.

TABLE 6.

APPLIED LOAD AT FIRST SLIP AT DIFFERENT POINTS OF BAR.

Applied loads are given in units of 1000 lb.
All beams were tested on a 6-ft. span. The loads given in the table cause a slip of about 0.0002 in. at the points indicated.

Beam No.	Reinforcement	Loads Apart ft.	Applied Load at First Slip Indicated by Instruments Number								
			N End	6 33 in. N. of Middle	4 24 in. N. of Middle	2 12 in. N. of Middle	1 Middle	3 12 in. S. of Middle	5 24 in. S. of Middle	7 33 in. S. of Middle	S End
1052.6	1-in.plain round	2	14	14	12	—	—	—	14	14	14
1056.2	do.	2	16	14	8	4	6	6	8	15	12
1057.2	do.	$2\frac{1}{3}$	12	12	8	4	6	8	4	12	12
1058.2	do.	3	10	10	8	4	4	4	4	11	11
1059.2	do.	$3\frac{1}{3}$	10	10	4	10	2	4	4	8	8
1060.3	do.	4	16	18	10	6	—	8	10	16	16
1046.2	1-in. square bar	2	10	10	4	6	—	4	6	10	10
1046.4	do.	2	10	8	8	—	4	4	6	8	13
1047.1	1-in. sq. twisted	2	10	14	6	4	4	6	6	15	15
1047.2 1047.3	do.	2	10	16	4	4	—	4	6	16	17
1061.5	1-in.rnd.threaded	2	11	10	10	4	2	6	13	10	14
1061.6	do.	2	16	14	6	6	—	4	4	10	11
1063.3	do.	2	19	19	8	8	—	8	8	15	8
1064.2	do.	2	10	8*	4+	2	4	2	2+	6*	10
1064.3	do.	2	10	10	6	4	—	4	8	10	10
1048.3	$1\frac{1}{8}$ corrugated	2	16	16	2	2	—	2	6	8	16
1048.4	round	2	10	10	4	4	2	2	2	—	8

+ Instruments No. 4, and 5 were placed 18 in. north of middle.
* Instruments No. 6, and 7 were placed 30 in. south of middle.

TABLE 7.

LOG OF A TYPICAL BEAM TEST.

Beam No. 1058.3 6 ft. 6 in. long. Loaded at 1/3 points.
Reinforcement one 1-in. plain round bar.
1-2-4 concrete, machine-mixed: age at test 67 days.
See page 108 for curves showing the relation of slip at various points.

Load lb.	Center Deflection in.	Slip of Ends of Bar S	Slip of Ends of Bar N	Slip of Bar at Points 1 18 in.S	2 18 in.N	3 24 in.S	4 24 in.N	5 30 in.S	6 30 in.N	Bond Unit Stress lb. per sq.in.
0	0	0	0	0	0	0	0	0	0	—
2 000	0.003	0	0	0	0	0	0	0	0	—
4 000	.008	0	0	0.0002	0	0	0	0	0	—
6 000	.018	0	0	.0015	0.0003	0.0001	0.0002	0	0	—
8 000	.032	0.0001	0	.0028	.0019	.0007	.0007	0.0002	0.0001	160
10 000	.044	.0002	0	.0046	.0025	.0016	.0014	.0003	.0002	198
11 000	.050	.0002	0.0001	.0056	.0021	.0020	.0020	.0004	.0003	217
12 000	.057	.0003	.0001	.0065	.0016	.0028	.0030	.0009	.0003	235
13 000	.065	.0004	.0002	.0075	.0015	.0032	.0037	.0011	.0006	254
14 000	.071	.0005	.0003	.0085	.0026	.0040	.0045	.0015	.0010	273
15 000	.078	.0006	.0005	.0092	.0040	.0045	.0052	.0020	.0015	291
16 000	.085	.0008	.0010	.0105	.0051	.0055	.0065	.0025	.0023	310
17 000	.092	.0013	.0018	.0120	.0062	.0068	.0081	.0035	.0035	329
18 000	.102	.0025	.0039	.0140	.0070	.0084	.0112	.0050	.0065	348
18 600	.119	.0038	.0160	.0160	.0082	.0103	.0250	.0065	.0210	359

Beam failed by bond. Bar pulled out at N. end.

machine. The photograph Fig. 2 shows a specimen in the machine ready for test.

The rubber cushion tended to avoid the effect of shocks and vibration of the testing machine. The spherical bearing block permitted the bar to take a vertical position and prevented any bending due to the bar not being parallel to the axis of the cylinder.

In these tests the amount of slip of the free end of the bar was measured with an Ames extensometer, the plunger being placed in contact with the 1/4-in. projecting end of the bar. The instrument was mounted on a wooden yoke which was attached to the end of the concrete cylinder as shown in Fig. 2. After placing the instrument and adjusting it, the amount of slip was indicated without further manipulation. The load was applied continuously until the bar had slipped at least 0.1 in. The load corresponding to a slip of the free end of the bar of 0.0005, .001, .002, .005, .01, .02, .05, .075 and 0.1 in. were recorded. A sample log sheet for a pull-out test is given in Table 8. Two men were required to make a test of this kind: one man operated the testing machine and announced the loads at intervals, while the other watched the operation of the slip-measuring instrument and kept the notes of the tests.

FIG. 2.

VIEW OF PULL-OUT SPECIMEN IN

MACHINE READY TO BE TESTED.

Table 8.

LOG OF A TYPICAL PULL-OUT TEST.

Specimen No. 1055.4

1-in. plain round bar, embedded 8 in. in an 8-in. concrete cylinder.

1-2-4 concrete, hand-mixed; age 63 days.

Slip of Bar inches	Total Load lb.	Bond Unit Stress Lb. per sq.in.
0.0005	9 200	366
.001	11 200	447
.002	12 600	502
.005	14 100	562
.010	14 600	582
.015	14 800	590
.020	14 000	568
.030	13 400	534
.050	12 100	483
.075	10 800	431
0.100	9 700	386

III. EXPERIMENTAL DATA AND DISCUSSION.

12. Classification of Tests.—This series of tests consists of 75 reinforced concrete beams 186 pull-out specimens and 129 6-in. cubes. Twenty-one beams, each reinforced with one 1-in. round longitudinal bar, were tested on a 6-ft. span. Three of these were reinforced with four 3/8-in. auxiliary rods at the ends. Nine were tested with the loads applied at the one-third points. In order to study the effect of changes in distance between load points and the supports three beams were tested on 6-ft. span with each of the following distances between loads: 2 ft., 2 1/2 ft., 3 ft., 3 1/2 ft. and 4 ft.

The effect due to the difference in placing the longitudinal reinforcement consisting of square bars, was determined by placing the side of the reinforcing bar horizontal and vertical in three beams, and placing the bars on edge in three beams. In three beams 1-in. square bars twisted one twist per foot were used in order to study the effect of twisted bars on bond resistance.

Bars consisting of 1-in. plain rounds threaded from 9 to 27 in. at each end were used in 15 beams to find the effect on the bond stresses developed. In three of the beams with 27 in. threaded ends the rods were polished throughout the middle 2 ft.

The effect of distributing the steel in a number of smaller bars was studied by testing 3 beams reinforced with three 3/4-in. rounds, and four 5/8-in. rounds. These were tested on a 6-ft. span. Six beams reinforced with 1 1/8-in. corrugated rounds were tested on a 6-ft. span, and two on a 10-ft. span. Three of the 10-ft.

beams reinfoced with 1-in. rounds were not tested in time to be included in this report.

The slip of the bar at various points along the beam was measured in thirty-one tests.

13. Computation of Stresses.—The unit bond stress in the reinforced concrete beams was calculated by means of the equation $u = \frac{V}{m\ o\ d'}$, in which V = total end shear due to the applied load and the weight of the beam, m = number of bars, o = perimeter of each bar, d' = the arm of the resisting moment due to the load on the beam. The values of d' vary with the amount of horizontal reinforcement. The values used are given in Table 9.

TABLE 9.

Values of d' used in computations of stresses in reinforced concrete beams.

Reinforcement per cent	d' inches
1.00	8.53
1.25	8.42
1.50	8.30
1.66	8.22

In this method of computing bond stress we consider the bond stress to be a direct function of the vertical shear on the beam, hence it would be zero at points between the load in beams loaded as in these tests, and have a uniform value outside the loads. It will be seen hereafter that this assumption is open to criticism.

The stress in the longitudinal reinforcement was calculated by equating the bending moment to the resisting moment, taking into account the weight of the beam. This is indicated by the equation $M = f_sAd'$, in which M is the maximum bending moment, A is the area of cross-section of longitudinal reinforcement, and f_s is the unit tensile stress in the steel. The bending moment due to the applied load for a beam loaded at the 1/3 points is $\frac{1}{6}Wl$, where W is the applied load and l is the span length.

The vertical shearing unit-stress was calculated by means of the equation $v = \frac{V}{bd'}$, where V is the end shear, b is the width of beam, and d' is the effective depth of the beam.

The unit bond stress in pull-out specimens is $u = \frac{P}{o\ h}$, where P is the total load on the bar at any time, o is the perimeter of the bar, and h is the length of embedment. In the case of the threaded bars the perimeter was considered equivalent to that of a round bar of the same average section as that of the threaded bars. The same method has been used in arriving at the perimeters of all kinds of deformed bars, or bars of irregular sections.

14. Explanation of Tables.—Table 4 gives data of the make-up of the test beams; Table 5 contains data of tests of the beams and the computed values of some of the principle stresses. The loads given in Table 5 are the loads applied by the testing machine and do not include the weight of the beam. The load at the first diagonal crack was the load noted when the first diagonal crack appeared. The loads corresponding to the first slip of the end of the bar have been recorded. The bond stress, stress in steel, and the vertical shear were corrected for the additional stresses pro-

duced by the weight of the beam. The failure of the beam as indicated in the table shows whether the beam failed by bond, diagonal tension, tension in steel or by a combination of these methods. Table 10 shows the unit bond stress between the concrete and the steel of the pull-out specimens for various amounts of slip of the free end of the bars. The table also gives the ratio of the average bond stress at each slip of the bar to the maximum bond stress developed.

It should be noted that the beams were generally made in pairs, and it often happened there were no pull-out specimens of the same numbers as the beams. If it is desired to compare a beam of this kind with the pull-out tests reference may be made to Table 4 where the numbers of the beams made together may be found.

A comparison of bond stresses as developed in the pull-out specimens from hand- and machine-mixed concrete is shown in Table 11 in which all the tests in Table 10 have been summarized. Table 12 contains the comparison of the bond stresses in the concrete beams and the pull-out specimens.

For the pull-out tests the averages are given for all tests in a group, for the highest values from each set of three specimens, for the lowest two of each set and for the lowest specimens for each set. It is felt that the proper basis for comparison of bond stresses in beam and pull-out tests is between the values for the beam at any amount of slip and the averages of the lowest two of the pull-out specimens. This still gives the beam test a slight advantage for the reason that in the beam test the higher value of two is automatically rejected since the end with the weaker bond resistance pulls out, while in the pull-out specimens we

reject the highest one of three tests.

Table 6 shows the applied load at the first slip at different points of the bar measured with the instruments placed at the ends and on the bottom of the beam.

15. Notes on Diagrams.—Curves were platted showing the center deflection of all the beams tested (75) under applied load, and the corresponding slip of the ends of the bar. These curves are shown on pages 80 to 105. Curves platted from the tests of 22 beams showing the relation between the applied load and slip of the bar measured along the bottom and at the ends of the beam are shown on pages 106 to 127. The line diagram of the beam at the bottom of the page shows the relative positions of the instruments, the distance between loads, and the positions of vertical stirrups. The curves on page 76 show the unit bond stresses at the various amounts of slip of the bar for the various bars used in the pull-out tests. The curves on page 77 give the relation between the maximum applied load and the loads at various amounts of slip of the bars used in the pull-out tests. For the beams tested with long continued load, curves were platted showing the relation between the slip of bar and the time in days that the load was maintained.

16. Strength of Concrete.—The compressive strength of concrete is less for hand-mixed concrete than for machine-mixed concrete. Tests of thirty-six 6-in. cubes of hand-mixed concrete gave a compressive strength of 2200 lb. per sq. in., of 93 cubes of machine-mixed concrete gave a value of 2800 lb. per sq. in. The test cubes were stored in damp sand. The average age at test was 63 days.

TABLE 10.

DETAILS OF PULL-OUT TESTS.

1-2-4 concrete, Universal portland cement, graded sand and crushed limestone.
The stresses are given in pounds per square inch.

Ref. No.	Age at Test Days	Bond in Pounds per Square Inch at Slip of (inches) .0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
					Hand-mixed Concrete.					
					5/8-in. round bars.					
		274	293	319	357	370	350	315	280	376
1050.4	70	319	370	389	407	420	407	383	337	420
		325	357	383	414	420	395	337	280	420
	Av.	306	340	363	393	403	384	345	299	405
Ratio to Max.		.755	.840	.895	.970	.995	.948	.852	.738	
					3/4-in. round bars.					
		388	419	462	504	531	530	483	403	542
1050.1	62	356	425	468	510	525	515	462	382	525
		388	446	472	493	505	478	414	350	505
	Av.	377	430	467	502	520	508	453	378	524
Ratio to Max.		.719	.820	.890	.957	.991	.968	.865	.727	
					1-in. round bars.					
		299	335	359	378	388	343	391	231	388
1051.1	67	323	339	368	390	407	418	399	354	418
		279	319	355	359	351	343	311	267	359
	Av.	300	331	361	375	382	368	367	284	386
Ratio to Max.		.777	.856	.935	.970	.990	.955	.950	.736	
		205	230	254	294	322	331	306	254	331
1053.1	59	254	282	303	339	355	346	307	254	359
		291	327	359	399	410	399	351	283	410
	Av.	250	279	305	344	362	359	321	267	366
Ratio to Max.		.683	.762	.832	.940	.989	.981	.878	.729	
		263	295	315	346	378	394	394	323	399
1054.1	60	355	386	402	430	442	422	368	322	442
		370	438	478	522	534	525	438	399	537
	Av.	329	373	398	433	451	447	400	348	459
Ratio to Max.		.717	.813	.865	.945	.982	.975	.872	.758	

TABLE 10. Continued.

Ref. No.	Age at Test Days	Bond in Pounds per Square Inch at slip of (inches) .0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
		343	411	442	467	470	431	371	303	470
1055.1	64	351	418	438	478	399	347	299	243	378
		339	363	371	379	382	359	299	239	382
	Av.	344	397	417	441	417	379	323	262	443
Ratio to Max.		.775	.895	.943	.993	.941	.855	.727	.591	
		263	295	315	346	378	394	394	323	399
1055.4	63	355	386	402	430	442	422	368	322	442
		370	438	478	522	534	525	478	399	537
	Av.	329	373	398	433	451	447	413	348	459
Ratio to Max.		.716	.812	.866	.942	.980	.972	.898	.757	
		319	438	538	582	562	542	470	398	582
1055.7	62	398	490	570	598	518	490	443	387	598
		299	399	462	502	506	466	399	319	506
	Av.	339	442	527	561	529	499	437	368	562
Ratio to Max.		.603	.785	.940	.999	.940	.890	.780	.656	
		299	410	438	458	466	438	399	351	466
1056.1	66	335	375	390	405	410	370	319	251	410
		351	430	454	478	486	442	375	311	486
	Av.	332	405	427	447	454	417	364	304	454
Ratio to Max.		.731	.891	.940	.985	1.00	.919	.802	.669	
		399	510	574	620	625	585	494	422	625
1059.1	64	426	486	510	518	518	478	407	347	518
		438	578	609	630	610	577	518	457	630
	Av.	421	525	564	586	584	547	473	409	591
Ratio to Max.		.712	.887	.951	.991	.989	.925	.800	.692	
1-in. square bars.										
		194	204	209	225	238	238	225	219	244
1046.1	60	263	297	312	350	381	393	378	347	397
		241	273	303	344	359	359	344	303	366
	Av.	233	258	275	306	326	330	316	289	336
Ratio to Max.		.694	.768	.820	.911	.971	.982	.942	.860	
		194	216	232	276	315	332	316	272	334
1046.4	61	200	225	250	297	328	341	328	291	344
		183	209	244	297	328	341	322	288	341
	Av.	192	217	242	290	323	338	322	284	340
Ratio to Max.		.565	.638	.712	.853	.950	.994	.947	.835	
1-in. square twisted bar.										
		241	262	290	330	355	364	395	—	417
1047.1	69	272	278	307	356	372	375	387	444	453
		231	275	313	360	394	407	443	522	533
	Av.	248	272	303	349	374	382	408	—	468
Ratio to Max.		.530	.581	.647	.746	.800	.816	.821		

TABLE 10. Continued.

Ref. No.	Age at Test Days	.0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
		Bond in Pounds per Square Inch at Slip of (inches)								
				1-1/8-in. corrugated round.						
		460	572	692	740	722	—	—	—	740
1048.1	64	396	544	622	670	678	—	—	—	678
		343	478	625	742	790	825	—	—	825
	Av.	400	531	646	717	730				781
Ratio to Max.		.512	.680	.827	.919	.935				
		448	590	715	805	822	—	—	—	822
1048.4	62	403	485	569	655	678	608	495	—	682
		340	467	537	622	660	586	473	—	660
	Av.	397	514	607	694	720	—	—	—	721
Ratio to Max.		.550	.713	.842	.963	.999				
		314	437	482	520	548	587	—	—	614
1049.1	68	401	473	519	573	591	609	—	—	616
		351	424	470	519	541	531	—	—	531
	Av.	355	445	490	537	560	576			620
Ratio to Max.		.572	.717	.790	.865	.903	.928			
				1-in. round bars, threaded.						
		253	276	400	477	563	629	400	—	629
1061.1	63	229	296	333	400	491	596	486	—	619
		257	309	348	381	428	505	367	—	524
	Av.	246	294	360	419	494	577	418		591
Ratio to Max.		.416	.497	.608	.710	.835	.975	.708		
		448	510	534	—	428	—	286	171	534
1061.4	68	414	521	526	470	414	193	192	—	526
		414	515	596	610	428	—	276	—	610
	Av.	425	515	552	540	423		251		557
Ratio to Max.		.763	.925	.991	.969	.758		.451		
				Machine-mixed Concrete.						
				5/8-in. round bars.						
		433	472	497	542	560	547	485	402	568
1050.5	63	376	510	542	567	580	542	465	414	580
		523	574	593	626	618	586	516	440	626
	Av.	444	529	544	578	588	558	489	419	591
Ratio to Max.		.751	.892	.919	.980	.992	.941	.827	.710	
		380	460	515	552	558	515	447	350	558
1050.6	61	509	572	610	641	647	602	490	415	647
		239	271	289	302	277	254	227	189	302
	Av.	376	434	471	498	494	457	388	318	502
Ratio to Max.		.749	.865	.936	.990	.985	.910	.772	.633	

TABLE 10. Continued.

Ref. No.	Age at Test Days	Bond in Pounds per Square Inch at Slip of (inches) .0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
				3/4-in. round bars.						
		388	420	448	474	485	479	432	377	485
1050.2	67	408	441	468	488	315	505	457	393	521
		414	473	500	536	552	536	477	404	552
	Av.	403	445	472	499	517	507	455	391	519
Ratio to Max.		.777	.856	.910	.962	.999	.980	.876	.752	
		350	485	517	563	583	572	517	428	583
1050.3	59	488	612	707	739	728	712	638	547	739
		450	541	577	597	603	593	537	455	603
	Av.	429	546	600	633	638	626	564	477	642
Ratio to Max.		.668	.850	.935	.980	.995	.975	.880	.745	
				1-in. round bars.						
		233	263	291	318	341	356	349	314	356
1051.2	60	274	283	294	307	323	323	303	282	327
		262	278	298	323	334	343	318	275	343
	Av.	256	275	294	316	333	341	323	290	342
Ratio to Max.		.748	.805	.860	.924	.975	.999	.945	.848	
		335	406	429	465	485	482	445	375	488
1051.3	65	346	418	446	482	494	476	422	370	494
		339	402	425	445	457	441	402	335	457
	Av.	340	409	433	464	479	466	423	360	480
Ratio to Max.		.708	.853	.902	.967	.999	.970	.881	.750	
		311	371	391	407	414	378	331	287	414
1052.2	66	319	359	378	399	383	374	335	279	399
		319	358	378	395	403	382	339	287	403
	Av.	316	363	382	400	400	378	335	284	405
Ratio to Max.		.780	.897	.943	.988	.988	.934	.828	.702	
		274	314	341	368	376	361	314	263	376
1052.5	71	319	335	347	359	343	335	303	255	359
		329	392	440	487	510	492	433	356	510
	Av.	307	347	376	405	409	399	350	291	415
Ratio to Max.		.740	.836	.906	.976	.987	.961	.844	.701	
		335	386	415	434	442	430	382	327	442
1052.6	71	295	335	338	350	358	342	310	267	358
		295	322	327	334	342	327	311	271	342
	Av.	308	348	360	373	381	366	334	288	381
Ratio to Max.		.807	.914	.945	.979	1.00	.960	.877	.756	

TABLE 10. Continued.

Ref. No.	Age at Test Days	Bond in Pounds per Square Inch at Slip of (inches) .0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
		314	388	392	413	424	392	352	317	424
1053.2	63	343	358	371	398	407	391	346	290	407
		315	331	343	358	370	351	330	295	370
	Av.	324	359	369	389	400	378	343	301	400
Ratio to Max.		.810	.898	.922	.972	1.00	.945	.858	.752	
		356	383	410	448	472	487	440	383	483
1054.2	65	291	350	382	418	442	454	426	——	454
		358	486	557	605	628	628	568	493	637
	Av.	335	406	450	490	514	523	478	438	525
Ratio to Max.		.637	.774	.857	.933	.979	.998	.910	.835	
		422	534	577	614	621	594	542	458	621
1054.3	64	370	449	513	540	538	532	476	402	540
		454	546	592	616	628	616	454	473	628
	Av.	415	509	561	590	596	581	491	444	596
Ratio to Max.		.696	.855	.941	.990	1.00	.975	.824	.746	
		434	534	617	677	689	670	602	522	689
1055.3	82	314	382	430	454	466	450	402	350	466
		343	440	468	508	525	504	464	391	525
	Av.	364	452	505	546	560	541	489	421	560
Ratio to Max.		.650	.807	.901	.975	1.00	.965	.932	.752	
		276	354	374	417	434	429	394	335	434
1055.6	81	338	437	474	522	534	522	465	398	537
		341	426	492	515	520	508	465	388	520
	Av.	318	406	447	485	496	486	441	370	497
Ratio to Max.		.640	.815	.880	.975	.996	.976	.886	.744	
		225	250	268	284	295	291	279	244	295
1055.8	64	335	390	411	438	446	438	402	358	472
		331	403	435	460	472	456	423	371	478
	Av.	297	348	371	394	404	395	368	324	415
Ratio to Max.		.715	.814	.894	.925	.972	.926	.896	.770	
		266	303	310	339	350	343	334	294	350
1055.9	65	239	295	319	339	351	334	311	267	351
		251	279	299	331	343	338	307	257	347
	Av.	252	292	309	336	348	338	317	273	349
Ratio to Max.		.722	.836	.885	.962	.997	.968	.909	.782	
		323	371	394	415	418	407	366	331	418
1056.2	69	323	351	362	379	383	367	331	311	383
		290	339	351	371	375	335	303	267	375
	Av.	312	354	369	388	392	369	333	303	392
Ratio to Max.		.796	.903	.941	.990	1.00	.940	.850	.772	

TABLE 10. Continued.

Ref. No.	Age at Test Days	.0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
		Bond in Pounds per Square Inch at Slip of (inches)								
		300	407	438	478	498	490	450	382	502
1056.3	64	231	327	338	366	378	375	358	307	383
	Av.	266	367	388	422	438	433	404	345	443
Ratio to Max.		.601	.828	.876	.955	.990	.977	.913	.779	
		239	271	287	307	319	323	303	267	323
1057.3	64	239	271	279	303	315	319	303	279	319
		243	283	299	315	323	315	295	255	323
	Av.	240	275	288	308	319	319	300	267	322
Ratio to Max.		.745	.854	.863	.956	.990	.990	.931	.829	
		251	263	267	271	275	255	239	219	275
1058.2	68	197	213	221	225	213	209	197	173	225
		223	247	259	263	255	252	241	219	263
	Av.	224	241	249	253	248	239	226	204	254
Ratio to Max.		.882	.950	.980	.995	.975	.940	.890	.803	
		143	146	148	154	162	169	173	161	178
1059.2	60	132	139	143	163	172	179	167	159	179
		147	159	172	183	188	178	168	147	188
	Av.	141	148	154	167	175	175	169	156	182
Ratio to Max.		.774	.813	.845	.917	.962	.962	.926	.857	
		299	377	423	427	418	403	361	318	427
1059.3	64	291	371	407	438	447	430	386	334	447
		311	338	358	366	374	358	338	295	374
	Av.	300	362	396	410	413	397	362	316	416
Ratio to Max.		.722	.871	.952	.986	.994	.911	.871	.760	
		395	458	478	482	447	423	374	303	482
1060.2	64	363	517	614	673	690	670	597	537	690
		466	546	606	626	601	577	510	438	626
	Av.	408	507	566	594	579	557	494	426	599
Ratio to Max.		.683	.845	.945	.990	.965	.930	.826	.710	
		446	522	562	605	622	597	534	455	622
1060.3	64	351	466	534	582	605	577	517	438	605
		357	412	437	480	512	507	465	399	512
	Av.	385	467	511	556	579	560	505	431	579
Ratio to Max.		.665	.807	.881	.910	1.00	.966	.872	.743	
		1-in. square bars.								
		219	259	291	322	341	319	297	278	341
1046.2	69	226	250	265	271	254	290	302	290	302
		161	164	173	179	195	204	213	216	219
	Av.	202	224	243	257	263	271	271	261	287
Ratio to Max.		.703	.780	.847	.895	.917	.944	.944	.910	

TABLE 10. Continued.

Ref. No.	Age at Test Days	Bond in Pounds per Square Inch at Slip of (inches) .0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
		272	352	407	459	478	466	428	370	479
1046.3	59	293	383	428	460	428	380	348	308	460
		272	377	432	453	457	402	340	308	457
	Av.	279	371	422	457	454	416	372	329	465
Ratio to Max.		.600	.798	.909	.984	.976	.895	.800	.707	
		147	150	163	188	203	213	197	166	213
1046.5	69	195	216	238	268	280	281	265	232	286
		241	270	286	314	324	318	294	250	326
	Av.	194	212	229	256	269	271	252	216	275
Ratio to Max.		.705	.770	.832	.931	.979	.985	.915	.785	
		240	250	265	275	337	313	297	268	337
1046.6	65	228	278	300	340	346	334	293	247	346
		206	238	260	298	319	313	294	253	322
	Av.	225	255	275	304	334	320	294	256	335
Ratio to Max.		.672	.761	.821	.907	.997	.955	.877	.764	
		1-in. square twisted bars.								
		263	305	334	370	402	420	435	475	574
1047.2	71	268	313	344	397	438	468	524	563	563
		266	310	331	391	395	410	425	491	522
	Av.	266	309	336	386	412	433	461	510	556
Ratio to Max.		.478	.556	.605	.694	.742	.779	.829	.917	
		339	465	528	595	620	614	572	364	620
1047.3	59	265	309	330	361	374	386	403	——	485
		370	456	481	481	544	541	——	——	544
	Av.	325	410	446	479	513	517			549
Ratio to Max.		.591	.745	.810	.872	.934	.941			
		249	329	350	388	407	412	428	478	670
1047.3a	59	280	350	382	403	407	388	385	400	435
		335	397	442	487	520	532	548	283	548
	Av.	288	359	391	426	445	444	454	387	551
Ratio to Max.		.523	.652	.710	.772	.807	.807	.825	.702	
		1 1/8-in. corrugated rounds.								
		339	396	423	463	480	530	630	650	650
1048.2	66	344	413	455	518	584	640	638	——	675
		294	373	438	502	552	600	574	——	631
	Av.	326	391	439	494	539	590	614		652
Ratio to Max.		.500	.599	.673	.757	.826	.905	.942		

TABLE 10. Continued.

Ref. No.	Age at Test Days	.0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
		396	516	611	670	689	672	682	470	689
1048.3	66	392	537	622	675	700	707	530	312	707
		353	480	580	671	692	642	375	——	692
	Av.	380	511	604	672	694	674	529		696
Ratio to	Max.	.546	.735	.869	.966	.997	.969	.761		
		282	473	527	583	629	660	707	487	707
1048.5	65	380	463	522	594	653	692	705	484	705
		389	537	626	680	——	——	——	——	707
	Av.	350	491	558	619	641	676	706	485	706
Ratio to	Max.	.496	.695	.790	.877	.907	.957	1.00	.687	
		200	253	273	316	347	388	508	274	527
1048.6	65	343	423	470	520	557	600	625	——	633
		350	410	448	506	551	604	682	——	682
	Av.	298	362	397	447	485	531	605		614
Ratio to	Max.	.485	.589	.646	.727	.806	.864	.985		
		318	382	400	427	453	445	442	382	453
1049.2	69	307	360	382	396	403	410	458	548	548
		293	353	388	420	442	458	502	562	562
	Av.	306	365	390	414	433	438	467	497	521
Ratio to	Max.	.588	.702	.749	.795	.831	.845	.895	.956	
		317	373	424	460	483	510	575	413	575
1049.3	79	336	427	495	560	572	587	595	382	602
		442	555	635	682	622	576	456	346	682
	Av.	365	452	518	567	559	558	542	380	619
Ratio to	Max.	.590	.730	.836	.916	.903	.902	.875	.614	
		1-in. round bar, threaded.								
		310	324	343	362	423	540	493	318	564
1061.2	68	276	319	343	381	443	523	576	480	576
		257	334	372	419	462	490	453	286	495
	Av.	281	326	353	387	443	518	507	361	545
Ratio to	Max.	.516	.598	.648	.710	.795	.950	.930	.662	
		524	605	710	823	856	786	323	——	856
1061.3	71	452	719	881	990	1000	——	238	——	1000
		671	834	1000	1090	1100	510	338	——	1100
	Av.	549	719	864	968	985	648	300		985
Ratio to	Max.	.552	.730	.877	.983	1.00	.658	.305		

TABLE 10. Continued.

Ref. No.	Age at Test Days	Bond in Pounds per Square Inch at Slip of (inches) .0005	.001	.002	.005	.010	.020	.050	0.10	Maximum Bond Stress
		640	842	970	1010	963	——	——	——	1010
1061.5	64	519	712	905	1035	1067	1010	——	——	1067
		338	385	409	448	496	557	525	310	577
	Av.	499	646	761	830	842	784			884
Ratio to	Max.	.565	.731	.860	.938	.952	.886			
		267	315	381	457	491	477	477	192	485
1062.3	64	305	353	391	443	505	586	562	405	605
		362	415	478	560	588	603	449	256	613
	Av.	311	361	417	487	528	556	496	284	568
Ratio to	Max.	.547	.636	.735	.860	.930	.978	.873	.500	
		433	496	568	658	344	792	348	215	792
1063.2	63	310	405	477	572	634	677	668	530	687
		372	428	477	515	563	625	528	356	625
	Av.	372	443	507	582	647	698	515	367	701
Ratio to	Max.	.530	.632	.724	.830	.923	.995	.735	.523	
		600	710	776	810	852	——	——	——	919
1063.3	64	545	635	727	794	817	756	361	174	817
		652	862	981	1052	1100	——	——	——	1110
	Av.	599	736	828	885	923				949
Ratio to	Max.	.631	.775	.872	.932	.971				

TABLE 11.

SUMMARY OF PULL-OUT TESTS.

These specimens were made in sets of three for comparison with reinforced concrete beams made from the same batches.

1-2-4 concrete; Universal portland cement, graded sand, and crushed limestone.

The stresses given are averages expressed in pounds per square inch.

Kind and Size of Bar	Method of Mixing	No. of Tests	Age at Test Days	Bond Stress at Slip of .0005	.001	.002	.005	Maximum Bond Stress
5/8-in. plain round	Hand	3	66	306	340	363	393	405
do.	Machine	6	62	410	482	508	538	547
3/4-in. plain round	Hand	3	62	377	430	467	502	524
do.	Machine	6	63	416	496	536	566	581
1-in. plain round	Hand	24	63	330	391	425	453	465
do.	Machine	60	68	305	362	389	414	428
1-in. square bar	Hand	6	61	213	238	259	298	338
do.	Machine	12	66	225	266	292	319	341
1-in. square twisted§	Hand	3	69	248	272	303	349	468
do.	Machine	9	63	308	359	391	430	552
1-1/8-in. corr.round	Hand	9	65	384	497	581	649	707
do.	Machine	18	68	338	429	484	536	635
1-in. round threaded+	Hand	6	66	336	405	456	479	579
do.	Machine	18	66	435	539	622	689	774

§ One twist per foot.

+ Standard threads, 8 per inch.

TABLE 12.

SUMMARY OF BOND TEST DATA.

Stresses are given in pounds per square inch.
The values given are the averages for the classification under "characteristics".

Ref. No.	Characteristics	Number of Tests	Age Days	Bond Stress at Slip of (inches) 0.0005	.001	.002	.005	.01	Maximum Bond Stress
	Pull-out Tests 5/8-in. plain round bars								
1	All tests	9	64	358	411	436	466	494	499
2	Highest from each set	3		452	503	518	556	561	565
3	Lowest two from each set	6		337	394	424	455	461	467
4	Lowest from each set	3		297	312	335	400	402	415
	Beam Tests 5/8-in. plain round bars								
5	All beams	3	61	213	235	229*	241	248	255
	Pull-out Tests 3/4-in. plain round bars								
6	All tests	9	63	397	463	502	534	558	553
7	Highest from each set	3		430	507	559	595	604	611
8	Lowest two from each set	6		396	455	490	519	536	537
9	Lowest from each set	3		365	441	472	511	524	524
	Beam Tests 3/4-in. plain round bars								
10	All beams	3	60	212	233	246	264	274	274
	Pull-out Tests 1-in. plain rounds								
11	All Tests	84	65	317	376	407	433	432	446
12	Highest from each set	28		339	404	440	470	480	484
13	Lowest two from each set	56		300	355	380	404	408	418
14	Lowest from each set	28		283	336	354	376	384	391

TABLE 12. Continued.

Ref. No.	Characteristics	Number of Tests	Age Days	Bond Stress at Slip of (inches) 0.0005	.001	.002	.005	.01	Maximum Bond Stress
	Beam Tests 1-in. plain rounds.								
15	5'-6" Loads 1 2/3 ft. apart	3	64	312	339	346	358	383*	364
16	6'-6" " 2 " "	9	64	311	348	359	—	—	366
17	6'-6" " 2 1/2 " "	3	65	328	390	392	399	420*	407
18	6'-6" " 3 " "	3	66	267	292	308	320	356*	332
19	6'-6" " 3 1/2 " "	3	62	278	347	401	—	—	438
20	6'-6" " 4 " "	3	64	429	509	524	543	519*	551
21	7'-6" " 2 1/3 " "	1+	63	260	292	307	316	—	322
22	8'-6" " 2 2/3 " "	3	62	291	—	—	—	—	303
23	10'-6" " 3 1/3 " "	5	63	—	—	—	—	—	222
24	10'-6" " 6 " "	2	89	259	259	259	259	—	259
	Pull-out Tests 1-in. square bars.								
25	All tests	18	64	219	252	270	308	328	339
26	Highest from each set	6		244	285	312	352	366	372
27	Lowest two from each set	12		209	241	266	294	309	323
28	Lowest from each set	6		202	221	256	266	283	298
	Beam Tests 1-in. square bars.								
29	All beams	6	61	218	248	260	269	270	278
	Pull-out Tests 1-in. square twisted.								
30	All tests	12	64	278	315	347	389	436	500
31	Highest from each set	4		311	384	407	459	493	599
32	Lowest two from each set	8		254	325	351	386	407	496
33	Lowest from each set	4		252	301	325	363	382	464
	Beam Tests 1-in. square twisted bars.								
34	All beams	3	61	254	293	312	330	330	337

TABLE 12. Continued.

Ref. No.	Characteristics	Number of Tests	Age Days	Bond Stress at Slip of (inches) 0.0005	.001	.002	.005	.01	Maximum Bond Stress
	Pull-out Tests 1 1/8-in. corrugated round.								
35	All tests	27	67	361	463	532	593	595	671
36	Highest from each set	9		383	498	570	626	641	695
37	Lowest two from each set	18		332	424	490	548	575	630
38	Lowest from each set	9		303	398	470	534	548	605
	Beam Tests 1 1/8-in. corrugated rounds.								
39	6'-6" loads 2 ft. apart	6	63	333	380	423	451	473	475
40	10'-6" " 3 1/3 " "	2	62	341	——	——	——	——	370
	Pull-out Tests 1-in. round threaded.								
41	All tests	24	65	385	472	539	584	660	676
42	Highest from each set	8		473	576	670	735	757	810
43	Lowest two from each set	16		380	470	535	552	615	670
44	Lowest from each set	8		351	444	488	504	560	614
	Beam Tests 1-in. round threaded								
45	Threaded 27 in. each end	6	63	348	364	——	——	——	387
46	" 21 " " "	3	62	337	359	345*	387	——	421
47	" 15 " " "	3	61	397	——	——	——	——	443
48	" 9 " " "	3	63	283	360	419	——	——	432

* The average of two tests.

\+ In two of the 7-ft. beams slip of bar at ends was not observed. These beams have been omitted from this summary.

17. Phenomena of Pull-out Tests.—The pull-out specimens were tested under a progressively applied load. The specimen took the load very slowly at first, until a load of about 2000 lb. was applied, then the specimen took the load more rapidly until the maximum load was reached, then the load fell off gradually. The first noticeable slip of the bar occurred under a load of from 3000 to 5000 lb. depending upon the size and form of the bar, but as there may have been some deformation in the concrete block, the reading for first slip of free end of the bar was recorded when the instrument indicated a slip of 0.0005 in. The applied load at the first slip of the bar was about 70 per cent of the maximum. The slip of the bar for the maximum load was usually 0.01 in., in some cases it was slightly greater, but for the plain rounds the above is the average value. After a slip of 0.01 in., the bar pulled out very rapidly. In the corrugated bars, and the bars threaded the maximum load occurred under a slip of 0.010 to 0.020 in. The variation in this value is due to the splitting of the concrete block at or before the maximum load. After the maximum was passed the load fell off and in most cases only one or two more readings were obtained.

The maximum load for the 1-in. square twisted bars occurred under a very much greater slip than any other of the bars. This slip was usually about 0.075 to .10 in. The concrete block then split and the load dropped off suddenly.

18. Effect of Method of Mixing on Bond in Pull-out Specimens. The influence upon the bond stress in the pull-out tests due to different methods of mixing is in favor of the machine mixing. For

the 5/8-in. rounds, 3/4-in. rounds, 1-in. square, 1-in. square twisted, and 1-in. round threaded bars, the unit bond stresses were higher in the machine-mixed than in the hand-mixed concrete. The difference ranged from 10 per cent in 1-in. square bars to 30 per cent in 5/8-in. rounds. The maximum bond stress for the hand-mixed concrete was higher than the machine-mixed in the 1-in. plain round and 1 1/8-in. corrugated round bars. The difference was 10 per cent and 12 per cent respectively. In each case, the one having the highest bond stress at the beginning of the slip of the bar had the highest maximum bond stress.

19. Comparison of Bond Resistance in Beams and Pull-out Specimens.—In comparing the bond resistance of the beams with the pull-out specimens, the beams and their corresponding pull-out specimens are considered, the relative amount of slip of the bar being taken into account.

In the beams reinforced with four 5/8-in. rounds the bond stress at a slip of 0.0005 in. was 203 lb. per sq. in.; in the pull-out (the average of three tests) the bond stress was 444 lb. per sq. in. or 100 per cent greater at the slip of 0.002 in.; the bond stress in the beam was 241 lb. per sq. in.; and for the pull-out the value was 558 or 130 per cent greater. Another beam with the same reinforcement at the slip of 0.0005 the bond stress in the beam was 180 lb. per sq. in. and in the pull-out 376 lb. per sq. in. or 109 per cent greater. At the slip of 0.002 the bond stress in the beam was 195 lb. per sq. in. and for the pull-out tests the value was 471 lb. per sq. in., or 140 per cent greater. These two tests show a wide variation between the bond stresses in beams and

pull-out specimens than has usually been found in this series of tests. The bond stress in the beam is much smaller than in the pull-out, and the difference increases as the slip of the bar increases. At the maximum load the average bond stresses were 255 and 476 lb. per sq. in. respectively for beams and pull-out specimens reinforced with 5/8-in. rounds.

For one beam reinforced with three 3/4-in. plain rounds the bond stresses at a slip of 0.0005 in. were 235 and 377 lb. per sq. in. for the beam and pull-out specimens respectively, or a difference of 60 per cent in favor of the pull-out specimens. At the slip of 0.002 in. the bond stress for the beam is 278, and for the pull-out specimen 467 lb. per sq. in., a difference of 68 per cent.

Another beam with the same reinforcement, at the slip of the bar of 0.0005 in., the bond stress was 200, and for the pull-out it was 403 lb. per sq. in., a difference of 100 per cent. At the slip of 0.002 in. the bond stress in the beam was 217 lb. per sq. in. and for the pull-out 472 lb. per sq. in., a difference of 102 per cent. The maximum bond stress in the beam was 235 lb. per sq. in. as compared with 519 lb. per sq. in. for the pull-out test.

Two 6-ft. beams reinforced with 1-in. plain rounds loaded at 1/3 points gave an average bond stress of 309 lb. per sq. in. when the slip of the bar was 0.0005 in. The average value for six pull-out tests is 314 lb. per sq. in. At the slip of 0.002 in. the bond stress in the beams was 347 and for the pull-out tests 366 lb. per sq. in. In these tests the difference between the bond stresses for the same amount of end slip was very small, but the pull-out tests have somewhat the largest value.

It is evident from these tests that the maximum bond stresses developed in beam and pull-out tests are not the proper basis for comparison. For the beams reinforced with 5/8- and 3/4-in. rounds the pull-out specimens gave higher loads than the beams for the same amount of slip. For the beams reinforced with 1-in. rounds the bond stresses compare closely with those developed in the pull-out specimens with 8-in. embedment.

Six 6-ft. beams reinforced with 1 1/8-in. corrugated round bars loaded at the 1/3 points gave an average bond stress of 334 lb. per sq. in. when the slip of the bar was 0.0005, and 427 lb. per sq. in. when the slip of the bar was 0.002 in. Eighteen pull-out tests gave an average bond stress of 361 and 543 lb. per sq. in. at a slip of 0.0005 and 0.002 in. respectively, or a difference of 8 and 27 per cent. These tests show the same characteristics as mentioned above.

20. Phenomena of Reinforced Concrete Beam Tests.—The load was applied continuously until the first slip occurred at either end of the beam, when the machine was stopped at interval of 1000 lb. or 2000 lb. load. The beams took the applied load slowly at first, and then faster until the maximum load was reached. At first, vertical cracks opened up between the load points of the beam. These cracks extended up to about one-half the depth of the beam, and were symmetrical about the center. Later, diagonal cracks appeared outside the load points sloping upward and toward the middle of the beam, which in most cases caused the failure of the beam. The appearance of representative beams after test may be seen in Photographs in Fig. 3 to 11 inclusive.

The first noticeable slip of the ends of the bar for the 6-ft. beams that failed by bond occurred under an average applied load of 10 000 lb. In the case of the 5-ft., 7-ft., 8-ft., and 10-ft. beams the first slip was at loads of 11 000, 10 000, 8 000 and 11 000 lb. respectively.

The deflection of the beam at the center increased by large amounts after the first cracks appeared, until the maximum load was applied. This deflection varied with the span, the amount of longitudinal reinforcement and the position of the loads.

21. Manner of Failure of Reinforced Concrete Beams.—The manner of failure of each beam is indicated in Table 5. In the greater part of the tests the beam failed by bond between the concrete and steel, that is, the bar pulled out at one or both ends. In some cases, however, a combination of bond and diagonal tension resulted, as indicated by the relation of the slip at the ends of the bars and the appearance of diagonal cracks.

The appearance of representative beams after failure is shown in the photographs, Fig. 3 to 11 inclusive. The beams in each set have been grouped together. Points of application of the loads and the points of support are shown by vertical arrows. The numbers adjacent to the cracks indicate the points to which the cracks had opened for various loads in thousands of pounds. The numbers inside the circles indicate the points at which the instruments were placed on the bottom of the beam for measuring slip of the bar. In all cases the right of the photographs corresponds to the south end of the beams as tested.

The beams shown in Fig. 3 are 6-ft. beams and reinforced with 1-in. square twisted bars loaded at the 1/3 points. Failure of

these beams was by bond. Fig. 4 shows similar beams reinforced with 1 1/8-in. corrugated rounds. They bore about the same number and appearance of cracks.

The beams shown in Fig. 5 are 5-ft. beams loaded at 1/3 points reinforced with 1-in. plain rounds. Very few cracks were formed in these beams. Failure was by bond.

Fig. 6 shows 7-ft. beams reinforced with 1-in. plain rounds loaded at 1/3 points. 1053.1 and 1053.3 failed by bond, and 1053.2 failed by bond and diagonal tension.

Fig. 7 shows 6-ft. beams reinforced with 1-in. plain rounds loaded at 1/3 points. Beam No. 1056.1 represents a typical bond failure; No. 1056.2 failed by bond and tension in steel. Fig. 8 shows similar beams but the distance between loads is 3 1/2 ft. No. 1059.1 failed by tension in steel and the other two by bond. Fig. 9 shows similar beams with the loads 4 ft. apart. These failed by bond. There is a marked difference between the number and appearance of cracks in these three sets.

The beams in Fig. 10 are 6-ft. beams reinforced with three 3/4-in. plain rounds loaded at the 1/3 points. These failed by bond and diagonal tension. In this set an unusually large number of cracks were formed as compared with the 6-ft. beams in Fig. 7.

In Fig. 11 are shown 8-ft. beams reinforced with 1-in. plain round bars loaded at 1/3 points. These beams failed by tension in steel. These are characterized by the large number of cracks and may be taken as representative of the 10-ft. beams which also failed in tension.

22. <u>Bond on Plain Round Bars in Beam Tests</u>.—The nine tests (Item 16 in Table 12) on 6-ft. beams reinforced with one 1-in.

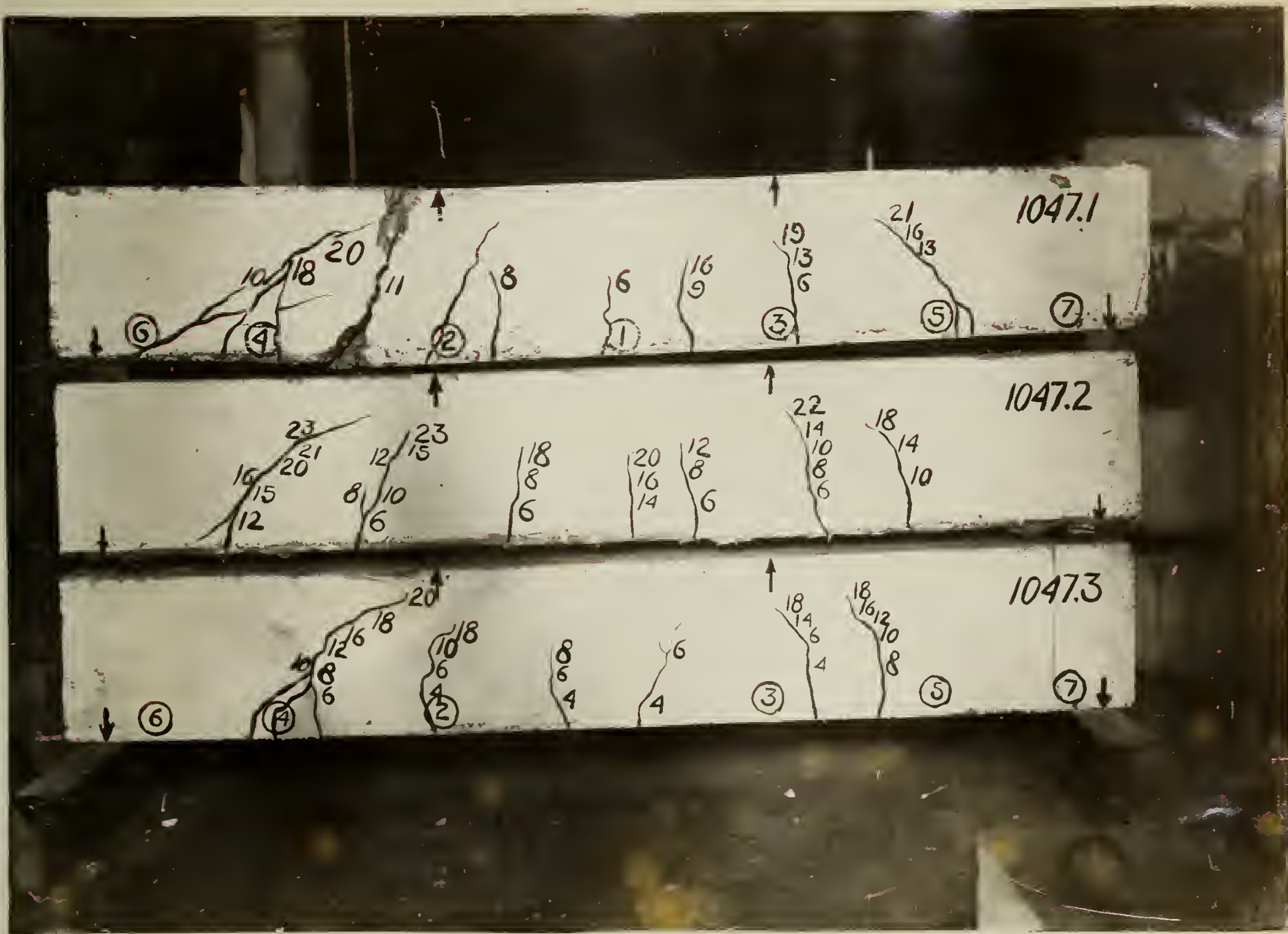


FIG. 3.

REINFORCEMENT 1-IN. SQUARE TWISTED BAR

TEST SPAN 6 FT.

DISTANCE BETWEEN LOADS 2 FT.

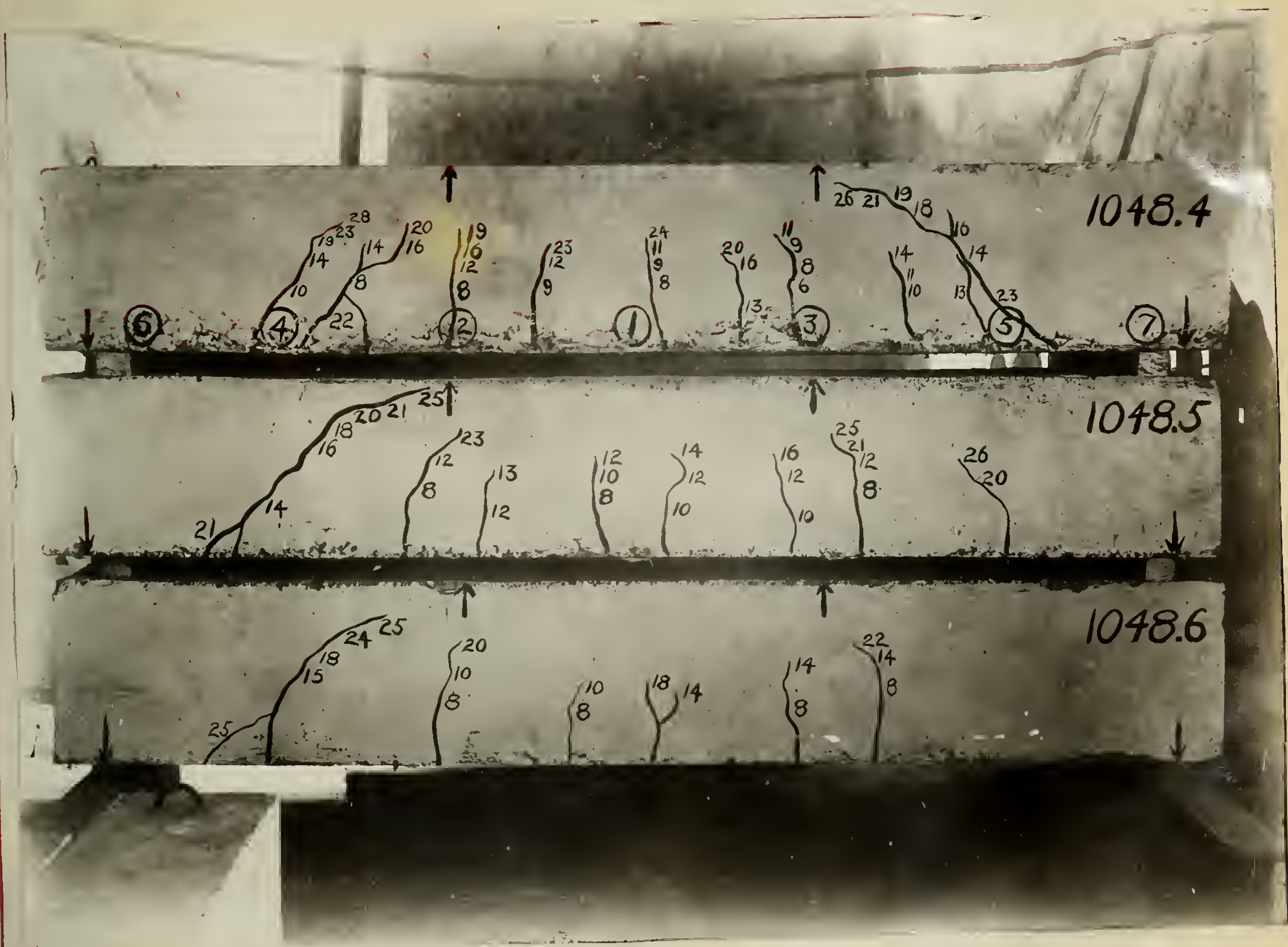


FIG. 4.

REINFORCEMENT 1 1/8-IN. CORRUGATED ROUND BAR

TEST SPAN 6 FT.

DISTANCE BETWEEN LOADS 2 FT.

FIG. 5.

REINFORCEMENT 1-IN. PLAIN ROUND

TEST SPAN 5 FT.

DISTANCE BETWEEN LOADS 1 2/3 FT.

FIG. 6.

REINFORCEMENT 1-IN. PLAIN ROUND BAR

TEST SPAN 7 FT.

DISTANCE BETWEEN LOADS 2 1/3 FT.

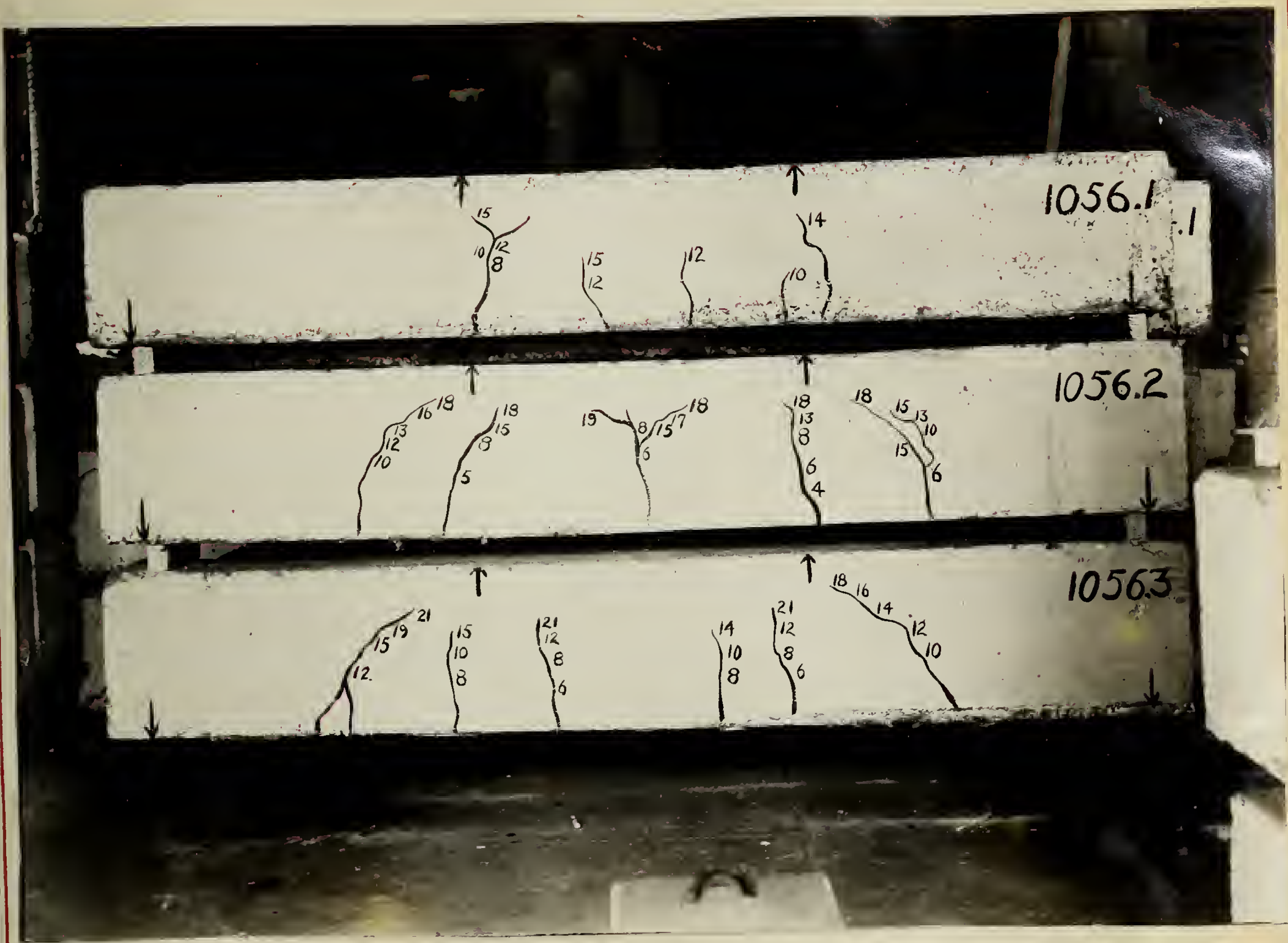


FIG. 7.

REINFORCEMENT 1-IN. PLAIN ROUND BAR

TEST SPAN 6 FT.

DISTANCE BETWEEN LOADS 2 FT.

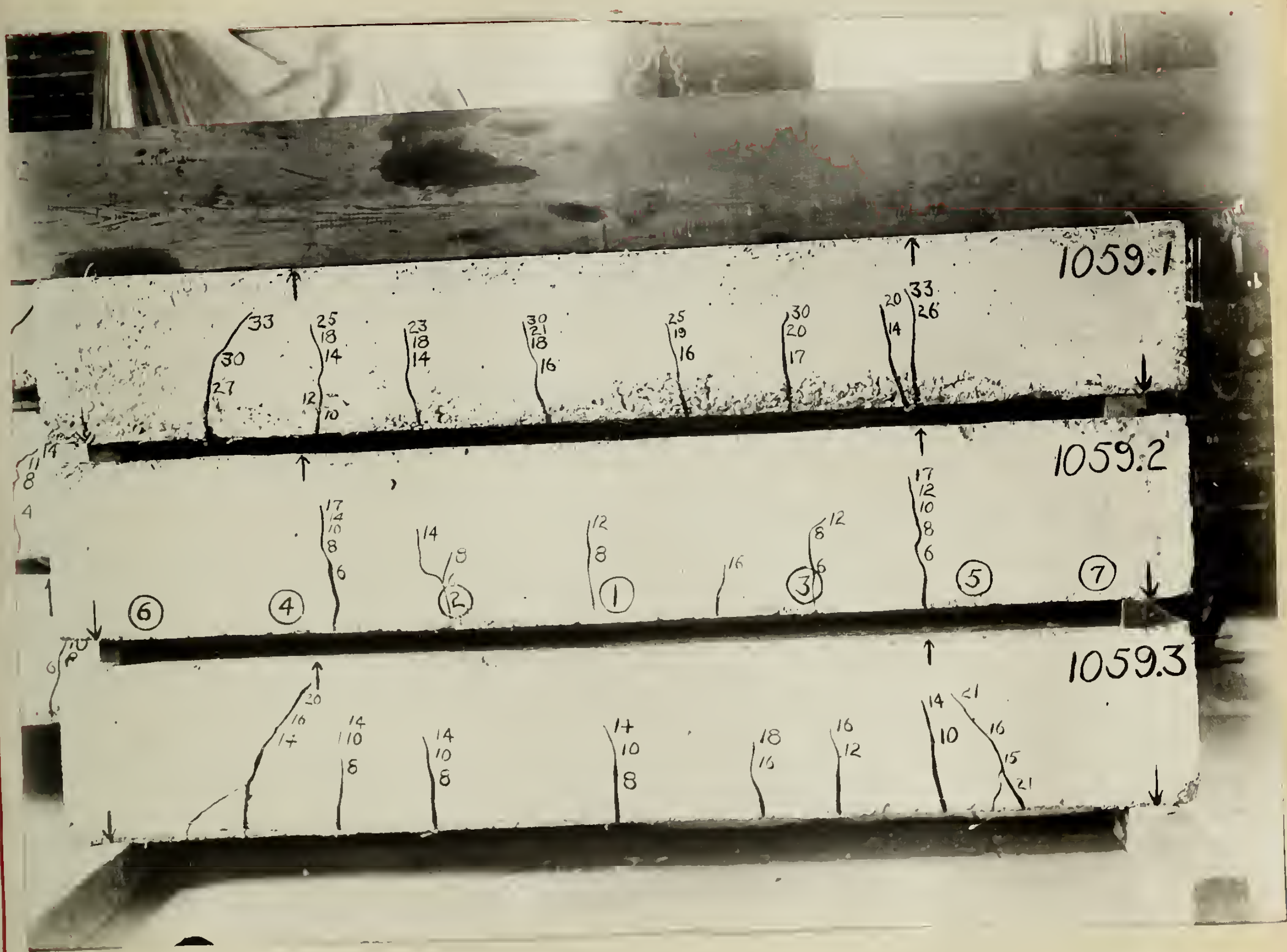


FIG. 8.

REINFORCEMENT 1-IN. PLAIN ROUND BAR

TEST SPAN 6 FT.

DISTANCE BETWEEN LOADS 3 1/2 FT.

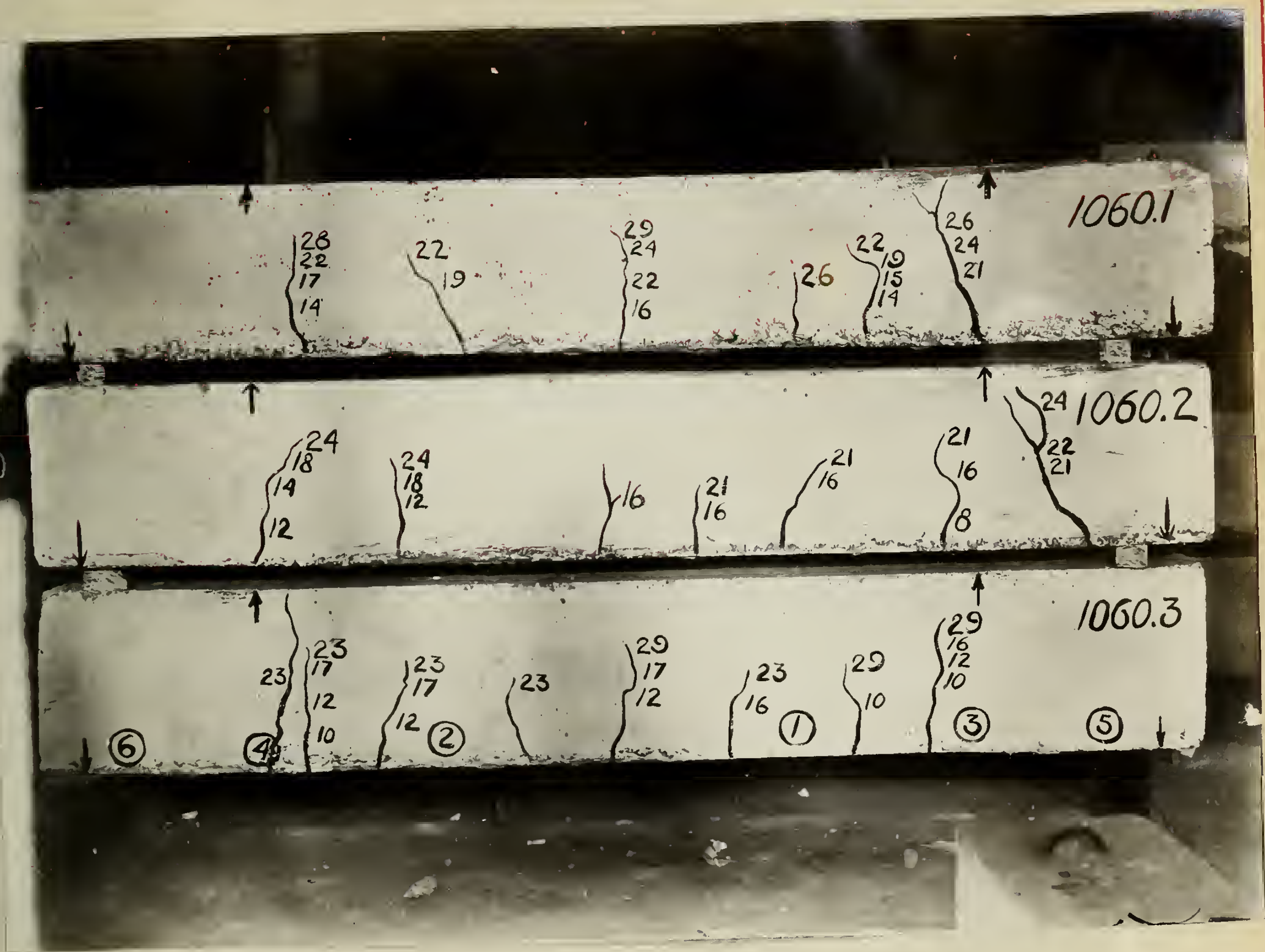


FIG. 9.

REINFORCEMENT 1-IN. PLAIN ROUND BAR

TEST SPAN 6 FT.

DISTANCE BETWEEN LOADS 4 FT.

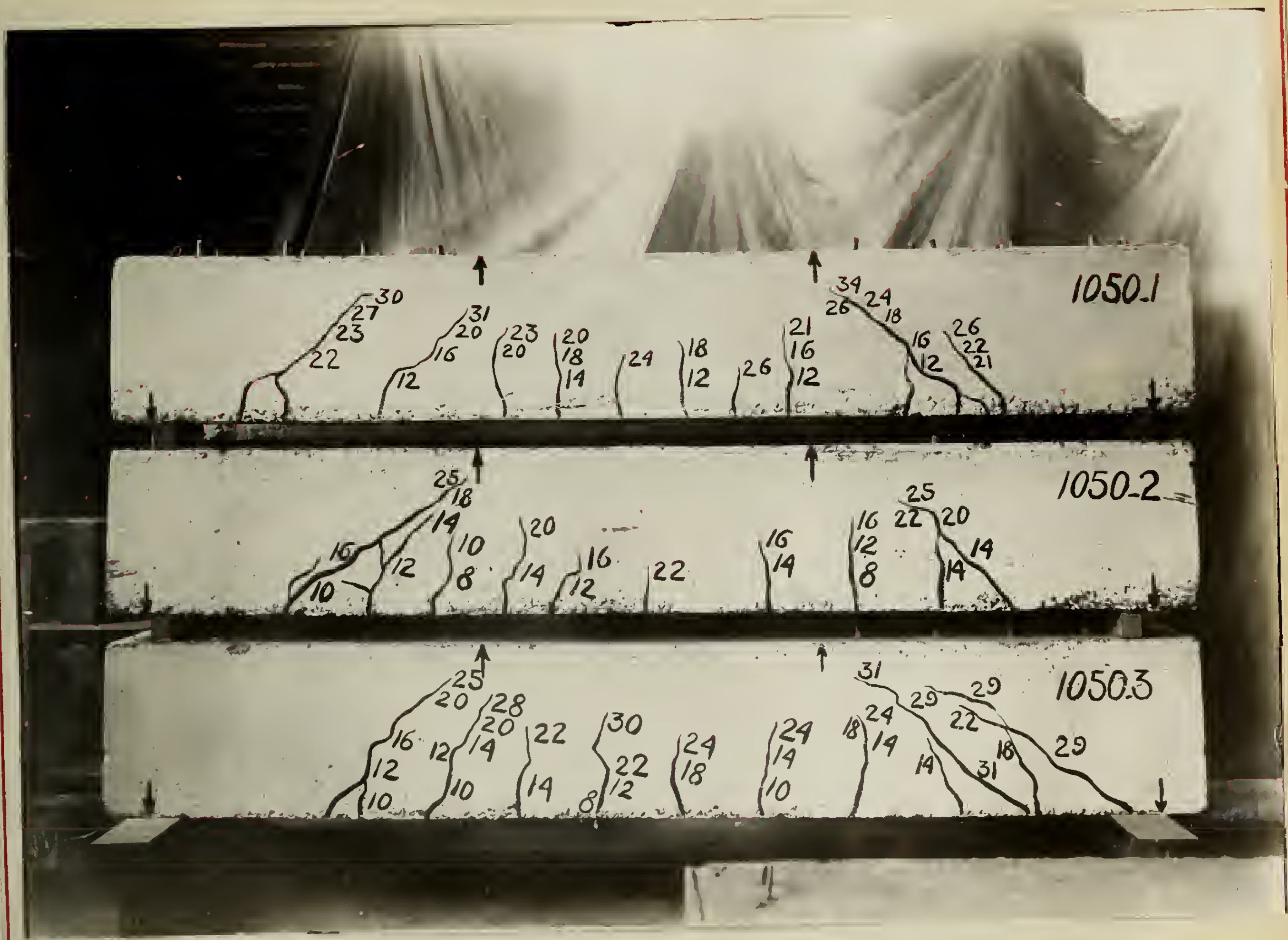


FIG. 10.

REINFORCEMENT 3 3/4-IN. PLAIN ROUND BARS

TEST SPAN 6 FT.

DISTANCE BETWEEN LOADS 2 FT.

FIG. 11.

REINFORCEMENT 1-IN. PLAIN ROUND BAR

TEST SPAN 8 FT.

DISTANCE BETWEEN LOADS 2 2/3 FT.

plain round bar and loaded at the 1/3 points of the span, may be taken as the basis for comparison with the other beams. For these beams slipping of the end of the bar began at an average bond stress of 311 lb. per sq. in. The bond stress at slip of the end of bar of 0.001 in. was 359 lb. per sq. in. The amounts of slip greater than 0.001 in could be observed in only a few of the tests. The table shows the maximum bond stress to be 366 lb. per sq. in., which is only a little greater than the value for a slip of 0.001 in. The bond stress at a slip of 0.001 in. is 98 per cent of the maximum stress for these specimens. It was seen in the pull-out specimens that the bond stress at a slip of 0.001 in. is about 80 per cent of the maximum bond stress. These considerations show that in comparing beam tests with pull-out tests, the relative amount of slip must be taken into account. As compared with the lowest two specimens from all sets of pull-out tests on 1-in. rounds it is seen that the unit bond stress is approximately the same for beginning of slip (300, and 311 lb. per sq. in.), but when a slip of 0.001 in. is reached the beam stresses begin to lag behind the pull-out tests.

Platted curves show the relation of slip of end of bars and the deflections for the beams mentioned above.

23. <u>Bond on Square Bars</u>.—The average maximum bond stress developed in six beams loaded at the 1/3 points was 278 lb. per sq. in. while similar beams with 1-in. round rods gave a bond stress of 366 lb. per sq. in.

24. <u>Effect of Method of Placing Square Bars</u>.—In placing the 1-in. square bars on edge, the highest bond stress from three beams

was 251 lb. per sq. in., as compared to a value of 302 lb. per sq. in., also from three beams where the bars were placed with sides horizontal. The bond stresses at beginning of slip were 159 and 165 lb. per sq. in. respectively. This shows a slight advantage, in favor of placing the bars with side horizontal. The average bond stresses for all the beams with 1-in. square bars is about the same as the average of the lowest two of each set of pull-out specimens for small amounts of slip. The maximum loads on the pull-out specimens is about 14 per cent greater than for the beams.

25. Bond on Square Twisted Bars.—Slip of bar in the beams reinforced with 1-in. square twisted bars begins at a bond stress of 254 lb. per sq. in. as compared with 218 for plain square bars and 311 lb. per sq. in. for 1-in. plain rounds. The maximum loads are 337, 278 and 366 lb. per sq. in. respectively. For the pull-out tests slip of bar begins at bond unit stresses of 254, 209, 300 lb. per sq. in. for 1-in. square twisted, 1-in. plain square and 1-in. plain rounds respectively. Maximum stresses in pull-out tests were 496, 323, and 418 lb. per sq. in. respectively. In these comparisons the average of the lowest two from each set of the pull-out tests have been used. Considering the large amount of slip necessary to develop the stress given for maximum bond stress on square twisted bars, it must be concluded that square twisted bars are of doubtful value when bond stresses are important.

26. Bond on Corrugated Bars.—The average maximum bond stress of six 6-ft. beams reinforced with 1 1/8-in. corrugated bars loaded at 1/3 points was 475 lb. per sq. in. The average of nine tests of 1-in. plain round bars gave a value of 366 lb. per sq. in.

The highest average bond stress developed by two 10-ft. beams loaded at the 1/3 points was 370 lb. per sq. in. Slip of bar begins in the beams reinforced with 1 1/8-in. corrugated rounds at an average bond stress of 336 lb. per sq. in. as compared with 311 lb. per sq. in. for 6-ft. beams reinforced with 1-in. plain round bars.

27. Bond on Threaded Bars.—The highest average bond stress of three tests each of 1-in. bars threaded 21, 15, and 9-in. at each end are 421, 443, and 432 lb. per sq. in. respectively. Nine tests on 1-in. plain rounds, gave an average value of bond stress of 366 lb. per sq. in. Slip of end of bar begins in these beams at unit bond stresses ranging from 283 to 397 lb. per sq. in., being highest for a threaded length of 15 in. The 15-in. length also gave the highest value for maximum bond stress,—443 lb. per sq. in.

The pull-out tests on threaded bars showed a beginning of slip at a unit bond stress of 380 as compared with 332 lb. per sq. in. for 1 1/8-in. corrugated rounds and 300 lb. per sq. in. for 1-in. plain rounds.

28. Effect of Polishing Middle of Bar on Bond Resistance.—In order to study the effect reducing the bond resistance throughout the middle thirds of the beams, three beams were made with round bars which were threaded 27 in. at each end and were polished throughout the middle third. These beams gave an average maximum bond stress of 387 lb. per sq. in. A similar bar threaded 27-in. at each end gave an average bond stress of 421 lb. per sq. in. Thus polishing the middle of the bar had a slight effect upon the bond stress, but since both sets of tests failed by tension in the steel, the effect of polishing the bar would perhaps have been

greater in a bond failure of the beams.

29. Effect of Relative Position of Loads.—The effect of the relative position of loads was studied in the testing of eighteen 6-ft. beams in which the distance between the loads was varied from 2 to 4 ft. An attempt was made to show the relation between the bond stress and the angle α, where α is the angle between the center line of the longitudinal reinforcement and a line drawn from a point on the center line of the reinforcement directly above the support, to the load point.

In the figure shown on page 75, the average stresses corresponding to beginning of slip and the average maximum bond stresses from the beam tests are plotted as ordinates and values of tan α as abscissae. Straight lines drawn through these points show that the average bond stresses increase for all stages of the tests as tan α increases. The bond stresses developed in the beams when the applied loads were 3 ft. apart seems to be erratic in comparison with the other values. This variation is in part due to the inclusion of one beam which gave very low values.

The line for maximum loads shows an increase of 45 per cent in the unit bond resistance due to a change in the value of tan α from 0.420 to 0.840. It is interesting to note that the lines for maximum loads and for beginning of slip if produced to the left would meet the axis of zero abscissae at about the same point corresponding to a unit bond stress of about 200 lb. per sq. in.

It is felt that these tests are most instructive in showing the relation between bond resistance and diagonal shearing resistance. The usual method of computing bond stress does not take into account the variations brought out in these tests.

30. Effect of Span Length.—The effect of the test span has a definite relation to the bond stress developed in the beam. When a beam is loaded at the 1/3 points the moment under the applied load, which is considered constant between loads, is equal to 2 Wl, where W is the applied load and l is the length of the test span in inches. Thus increasing l will increase the moment, and if a beam is designed to take a definite bending moment, W must necessarily be smaller. The bond stress which is a function of the end shear, which is equal to $\frac{W}{2}$, will therefore be smaller. All of the 8- and 10-ft. beams tested on 8- and 10-ft. span developed a very low bond stress, failure of the beam occurred by tension in the steel.

The deflection of the beam is much greater for the 8- and 10-ft. beams under the same applied loads as compared with the 6-ft. beams. Reference is made to the deflection curves plotted for these beams, attention being called to the increase of the scale for the deflection in inches.

31. Slip of Bars at Internal Points.—An interesting feature of this series of tests was the measurement of the slip of the bar at different points along the beam. The curves on pages 106 to 127 show conclusively that the slip of bar begins within the middle third, earlier than at points towards the ends and last at the ends. For the 6-ft. beams reinforced with 1-in. plain rounds the average applied load when slip of bar was first measured near the middle of the beam was 4000 lb., or 1/5 to 1/4 of the maximum load. Table 6 gives the applied loads at which the slip was first indicated at various points for the beams tested in this manner.

At points nearer the ends slip first occurred under a larger load, thus showing that the slip first occurs toward the middle of the beam and gradually moves towards the ends of the beams. The instruments which were attached 6-in. from each end gave about the same slip as that noted by the instruments at the ends of the bar.

The pointers of the instruments in some cases turned to the right, and in other cases to the left. This difference in rotation is probably due to the position of the instrument with respect to the steel plug and the crack in the beam. If the crack opened up between the instrument and plug, the instrument rotated in one direction, while on the other hand when the crack was outside of the plug and instrument, it turned in the opposite direction. The slip of the bar as determined by these readings was not the true slip of the bar, because it is evident that as soon as a tension crack opens up near the instrument a very large apparent slip will occur. The peculiar shape of some of the curves plotted on pages 106 to 127 are due to the cracks that opened up.

On the other hand, at points near the ends of the beam where the instruments are attached and where there are few cracks that interfere with the instrument, the slip of the bar would be more accurately indicated. It will be noted in Table 6 and in the load-slip curves for the beams that there is quite a similarity between the action of the two ends of the bar.

32. Distribution of Bond Stress Along the Length of Bar.— The pull-out tests indicate that as the bar is pulled out, the bond resistance is increased until a slip of about 0.01 in. is reached. In the case of plain round bars this increase of maximum load at first slip is about 30 per cent. We may assume that a somewhat

similar load holds in a bar in a reinforced concrete beam. This leads to the conclusion that high bond stresses are developed between the loads in beams loaded symmetrically at two points, and that the bond stress is not uniformly distributed over the portion of the bar outside the load points. The ordinary methods of computation of bond stress do not take these conditions into account, but assumes that there is no bond stress developed between the loads and that the stress is uniformly destributed along the bar outside of the load points. These tests do not show the exact distribution of bond stress along the bar, but they indicate that bond stress is developed much earlier at points just outside the loads and is always higher here (at least until the amount of slip exceeds about 0.01 in.) than at points near the ends. Reference to the curves for slip of bar in Beam tests No. 1051.2 shows a movement of the bar near the load points of 0.008 in. when the end of the bar has only begun to slip. If the stresses corresponding to certain amounts of slip follow the same law as was found in the pull-out tests we may say that the bond stress in the beam referred to above is about 97 per cent of the maximum resistance of a pull-out specimen at the load points and about 70 per cent near the ends of the bar. This might indicate that a higher bond stress is developed than is really present, but the tests show that after this stage of the test the bond stress is rapidly transmitted more and more toward the end of the beam, and the bar pulls out under a unit stress only a little higher than that causing first slip at the end of the bar.

33. Effect of Continued Load on Bond Resistance.—In the tests of Beams No. 1055.9 and 1055.8 the effect of long-continued load was observed. These beams were reinforced with one 1-in. plain round and were tested on a 10-ft. span with loads applied at two points 6 ft. apart. The load on the beam was maintained constant by a rest of sixteen small car-springs placed under the head of the testing machine. By this method, the load remained fairly constant although the beam deflected somewhat under the load. The maximum falling off of the load from day to day was 100 to 150 lb.

Beam No. 1055.9 was loaded in the usual way until a slip at the south end of the bar of 0.0004 in. was recorded. This slip came at an applied load of 16 000 lb., corresponding to a computed bond stress of 315 lb. per sq. in. This load was then maintained and readings of the amounts of slip at various points along the bar taken at frequent intervals. The bar pulled out at the south end under this load after an interval of about 36 hours. The beam was 85 days old when tested. The progress of the slip at several points is indicated in the diagram on page 78.

Beam No. 1055.8 was tested in the same way except that the application of load was discontinued as soon as the smallest perceptible amount of slip of the bar had occurred. At a load of 10 000 lb. the south end showed a slip which was estimated at 0.0002 in. Points 3 in. and 9 in. inside the south load showed slips of 0.0005 and 0.002 in. This load was allowed to remain on the beam.

Readings were taken at frequent intervals during the first 24 hours. After 24 hours the slips at the points indicated were

0.0008, 0.0011 and 0.0030 in. The beam was put under load on April 6, 1912, when it was 90 days old. A load of 10 000 lb. was continued for 33 days; after which time the load was increased 100 lb. each day up to the present time when the load is 11 500 lb. The changes in slip at the south end and at the two points just inside the south load are indicated in the figure on page 79. The readings taken on May 29, 1912, load 11 500 lb. showed 0.0084 in., 0.0098 in., and 0.128 in. for the south end and the points 3 in. and 6 in. inside the load respectively. The loading will be continued in this manner. For the first few days after the increasing of load began there was no appreciable change in the direction of the curves. After about 10 days, with 10 per cent increase in the load, the amount of slip began to increase. The slip in this beam is much more than would ordinarily be found before final failure occurs. The increase in strength of the concrete with age since the test began is thought to account for this difference. Tests on pull-out specimens have shown that the bond resistance increases with age over the original strength even after the bar has been repeatedly pulled out as much as 0.1 in. The condition of storage of the test specimens has an important bearing on this phenomenon.

34. <u>Effect of Method of Mixing on Reinforced Concrete Beams</u>. The influence upon the bond stress in the beam tests due to different methods of mixing the concrete is in favor of the hand-mixing except in the case of the 1-in. round bars where a value of 344 lb. per sq. in. was obtained, as compared with a value of 378 lb. per sq. in. in the machine-mixed concrete. The greatest difference in any case was about 50 to 75 lb. per sq. in.

35. Relation of First Diagonal Crack and First Slip of End of Bar in Beam Tests.—The relation of slip at end of bar and the appearance of the first diagonal crack may be studied by reference to Table 5. The load at the first diagonal crack varied from 4 000 to 21 000 lb., depending mostly upon span length and the distance between the load and support. The close relation between the loads causing the diagonal cracks and beginning of slip of the end of bar indicates that there is an intimate connection between these phenomena. Tests made in 1911 indicate that bond resistance may be increased by increasing the resistance to diagonal tension by means of an increased amount of concrete below the bar. On the other hand, it has been found that the increasing of the bond resistance by the use of deformed bars or anchoring the ends of the bars has very little influence on the diagonal tension failures.

36. Effect of Auxiliary Reinforcement at Ends of Beam.—Three beams (No. 1052.4 - 5 - 6) were provided with additional bars at the ends, consisting of four 3/8-in. round bars in the form of long loops. The main longitudinal reinforcement of these beams consisted of one 1-in. plain round bar. The load at the first diagonal crack was very high as compared with the load on the beams without auxiliary bars. The highest average bond stress developed in these three beams was 371 lb. per sq. in., the average value of six beams not reinforced with the additional bars was 367 lb. per sq. in. The most noticeable effect due to the additional bars was the non-appearance of the diagonal cracks until very near the maximum. It will be seen by reference to the load-slip curves for one of these beams, page 81, that the auxiliary bars have an important influence on the slip of the bar with reference

to the adjacent concrete. The curves are much more regular than with any other beams.

37. Relation of Deflection of Beam to Slip of the Bar.— There seems to be a definite relation between the slip of the bar and the center deflection of the beam. The deflection curves for some of the beams show a decided bend when the bar first started to slip. It may be expected that an excessive slip of bar would make itself evident in the deflection curves.

38. Critical Bond Stress as Determined by the Slip of the Bar.—The bond stress which may be developed without danger of ultimately failing by bond was about 300 lb. per sq. in. in the beams reinforced with 1-in. round bars. This may be defined as the critical bond stress. In the beams reinforced with three 3/4-in. rounds and four 5/8-in. rounds, the critical bond stress ran lower than that of the beams with 1-in. round, with values of about 225 and 200 lb. per sq. in. respectively. The beams with 1 1/8-in. corrugated rounds reinforcement attained a much higher critical bond stress of about 400 lb. per sq. in.

39. Values of Bond Stress to be Used in Design.—Since, as mentioned in the introduction, the test beams were designed to develop high bond stresses, the beams seemed to attain a much higher bond stress before any evidences of failure were seen than 90 lb. per sq. in., which, according to Turneaure and Maurer's "Reinforced Concrete Construction" is usually used in design. The results obtained under the conditions present in these tests show that a bond stress of 100 lb. per sq. in. for round bars, and a value of 120 lb. per sq. in. for deformed bars would give a factor of safety of about

3 based on the critical bond stress in the beam tests.

40. Vertical Shearing Stresses in Beams.—The average vertical shearing stress in the beams with 1 per cent steel was about 165 lb. per sq. in., with 1 1/4 per cent reinforcement it was 172 lb. per sq. in., in those with 1 1/2 per cent steel it was 244 lb. per sq. in.; and in the beams reinforced with 1.66 per cent steel, the shearing stress reached a value of 36.5 lb. per sq. in. This seems to indicate that the vertical shear increases resistance as the per cent of steel is increased. However, the bond stresses developed by the beams with the higher percentages of reinforcement, are smaller than in the beams with smaller per cents of steel; hence it seems probable that the bond stresses have an important bearing on the shearing resistance of beams of this kind.

41. Stress in the Longitudinal Steel.—The tensile stress in the longitudinal reinforcement of the beams that failed under bond varied from 18 000 to 40 000 lb. per sq. in. For beams that failed by tension in the steel, the stress developed varied from 40 000 to 53 000 lb. per sq. in. In cases where the beams failed by bond and tension in steel, the stress in the steel ranged from 30 000 to 40 000 lb. per sq. in.

IV. CONCLUSIONS.

The principal conclusions from the foregoing discussion may be summarized as follows:

1. The compressive strength of concrete is less for hand-mixed than for machine-mixed concrete. Tests of thirty-six 6-in. cubes of hand-mixed concrete gave an average compressive strength of 2 200 lb. per sq. in., the average of 93 cubes of machine-mixed concrete gave a value of 2 800 lb. per sq. in. The test cubes were stored in damp sand. The average age at test was 63 days.

2. The applied load at the first slip of the bar in the pull-out tests was about 70 per cent of the maximum load. For the plain bars the slip of the free end of the bar for the maximum load was about 0.01 in. In the corrugated and threaded bars the maximum load occurred under a slip of about 0.010 to 0.020 in. The maximum load for the 1-in. square twisted bars occurred under a slip of the bar of about 0.075 to 0.10 in.

3. In comparing the bond stress in the beams with the pull-out tests, the relative amounts of slip of the bar must be taken into consideration. The tests indicate that at the first slip of the bar the bond stresses are about the same, but as the slip of the bar increases the bond stress in the beam is somewhat smaller than in the pull-out tests. In the case of beams reinforced with 1-in. plain round and 1-in. square bars and loaded at the 1/3 points, the maximum bond stress developed by the beams is 87 per cent of the maximum stresses developed in the pull-out tests, using the averages of the lowest two values in each set as a basis of comparison for

the pull-out tests.

4. The average maximum bond stress developed in six beams reinforced with square bars, and loaded at the 1/3 points was 278 lb. per sq. in., while similar beams with 1-in. round bars gave a bond stress of 366 lb. per sq. in.

5. The beams reinforced with 1-in. square bars with the sides horizontal gave a higher bond stress than in similar beams with the bar placed on edge. At the beginning of slip of the bar these stresses were 159 and 165 lb. per sq. in. respectively.

6. The slip of the bar in the beams reinforced with 1-in. square twisted bars began at a bond stress of 254 lb. per sq. in. as compared with 218 for plain square bars, and 311 lb. per sq. in. for 1-in. plain rounds. Considering the large amount of slip necessary to develop the maximum bond stress in the square twisted bars, it may be concluded that square twisted bars are of doubtful value when bond stresses are important.

7. In six 6-ft. beams reinforced with 1 1/8-in. corrugated bars loaded at the 1/3 points the average bond stress at first slip of the bar was 336 lb. per sq. in.; the maximum bond stress was 475 lb. per sq. in. The average of nine tests of 1-in. plain round bars gave a bond stress of 311 and 366 lb. per sq. in. respectively.

8. The beams reinforced with 1-in. plain round bars threaded 21, 15, and 9-in. at each end gave an average bond stress at first slip of the bar ranging from 283 to 397 lb. per sq. in. The maximum bond stress was 421, 443 and 432 lb. per sq. in. respectively. Similar tests on 1-in. plain rounds gave an average maximum bond stress of 366 lb. per sq. in.

9. The polishing of the bars between the threaded ends decreased the maximum bond stress 10 per cent as compared with similar beams in which the bar was not polished.

10. Tests on beams in which the distance between loads was varied shows that there is a definite relation between the bond stress and the angle α, where α is the angle between the center line of the longitudinal reinforcement and a line drawn from a point on the center line of the reinforcement directly above the support, to the load point. The curves platted showing the relation of tan α to the unit bond stresses developed show that as tan α increases the bond also increases for all stages of the test. Increasing the value of tan α 50 per cent increases the maximum bond resistance 45 per cent.

11. Tests show that first slip of the bar occurs toward the middle of the beam and gradually moves towards the ends. The large apparent slip of the bar near the middle of the beam was increased by tension cracks in the concrete that opened up between the steel plug and the instrument. At points near the ends of the beam where there are few cracks to interfere, the instrument will give a more accurate measure of the slip of the bar. For the 6-ft. beams reinforced with 1-in. plain rounds the average applied load when slip of bar was first measured was 4 000 lb., or 1/5 to 1/4 of the maximum applied load. This shows that slip of the bar occurs much earlier than has heretofore been thought.

12. The ordinary method of computing bond stress assumes that there is no bond stress developed between the loads in a beam loaded symmetrically at two points. Pull-out tests indicate that as the bar is pulled out the bond resistance increases until a slip

of 0.01 in. is reached. It is fair to assume that a similar condition holds in reinforced concrete beams and that high bond stresses are developed between the loads; and that the bond stress is not uniformly distributed over the portion of the bar outside the load points. Reference to the curves for the slip of bar in Beam No. 1051.2 shows a movement of the bar near the load points of 0.008 in. where the end of the bar had only begun to slip. If the stresses corresponding to certain amounts of slip follow the same law as was found in the pull-out tests we may say that the bond stress in the beam is about 97 per cent of the maximum resistance of a pull-out test at the load points and about 70 per cent near the ends of the bar at this stage of the test.

13. In Beam No. 1055.8 the continuation of the load that produced first slip of the ends of the bar, did not cause the beam to fail in the course of 33 days. The load was then increased 1 per cent each day. The slip of the bar in this beam was greater than would ordinarily be found before final failure occurs. After 48 days the beam was still taking load. This shows an increase in the bond resistance during the interval since loading began. Tests on pull-out specimens show that bond resistance increases with age.

14. The hand-mixed concrete gave the highest average bond stress in the beams, except for the 1-in. plain round bars where a value of 344 lb. per sq. in. was obtained as compared with a value of 378 lb. per sq. in. in the machine-mixed concrete. The difference generally was not greater than 50 to 75 lb. per sq. in.

For the pull-out tests the machine-mixed concrete gave a somewhat higher bond stress.

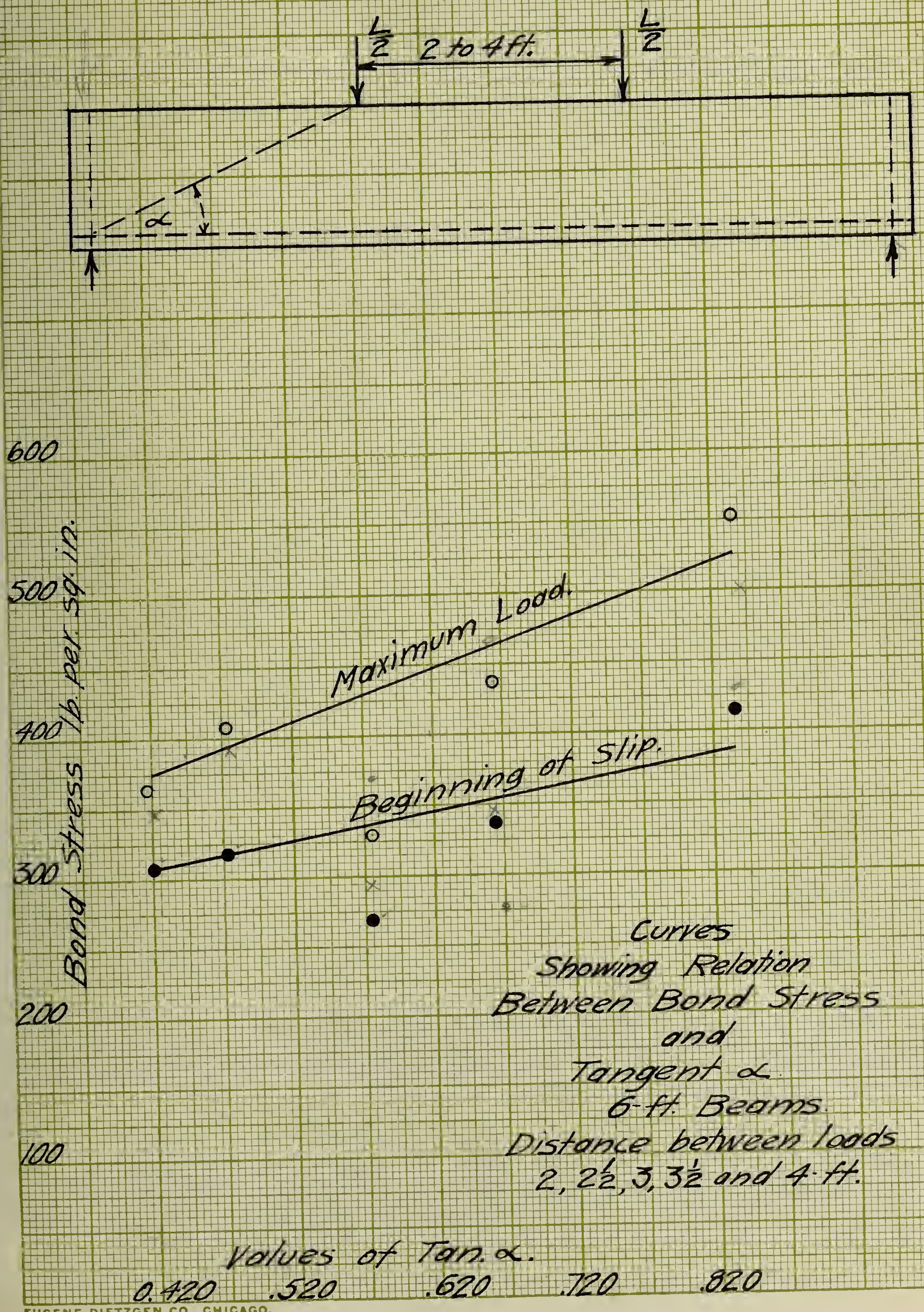
15. There is a close relation between the loads causing the

diagonal cracks and beginning of slip of the end of bar. Tests indicate that bond resistance may be increased by increasing the resistance to diagonal tension, but it has been found that increasing the bond resistance has very little influence on diagonal tension failures.

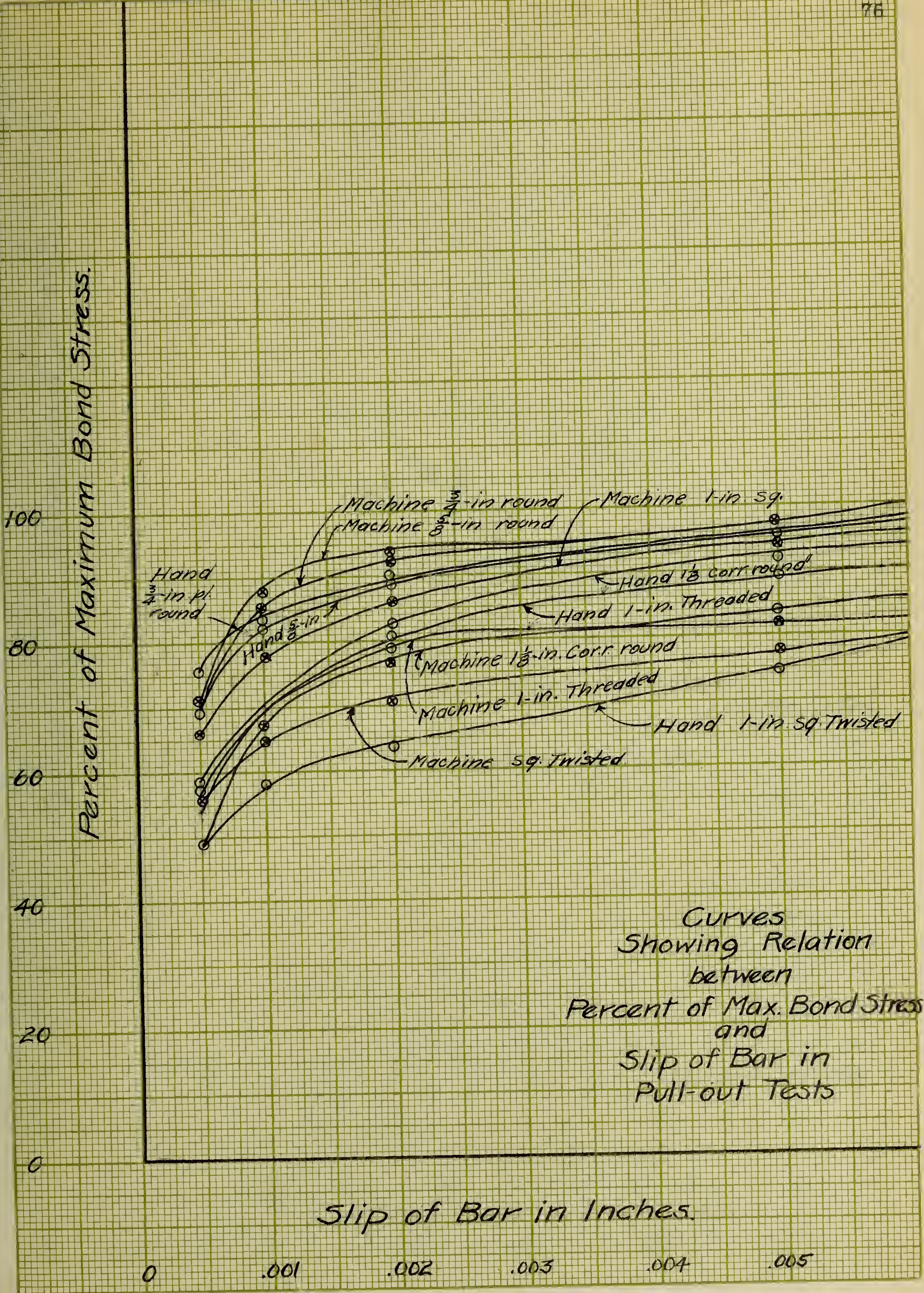
16. The auxiliary reinforcement in the ends of the beams, consisting of four 3/8-in. rounds, had a decided effect upon the appearance of diagonal cracks. The diagonal cracks did not appear until the beams were near the maximum load. The load-slip curves for these beams indicate the effect of the auxiliary bars, as shown by the regularity of the curves.

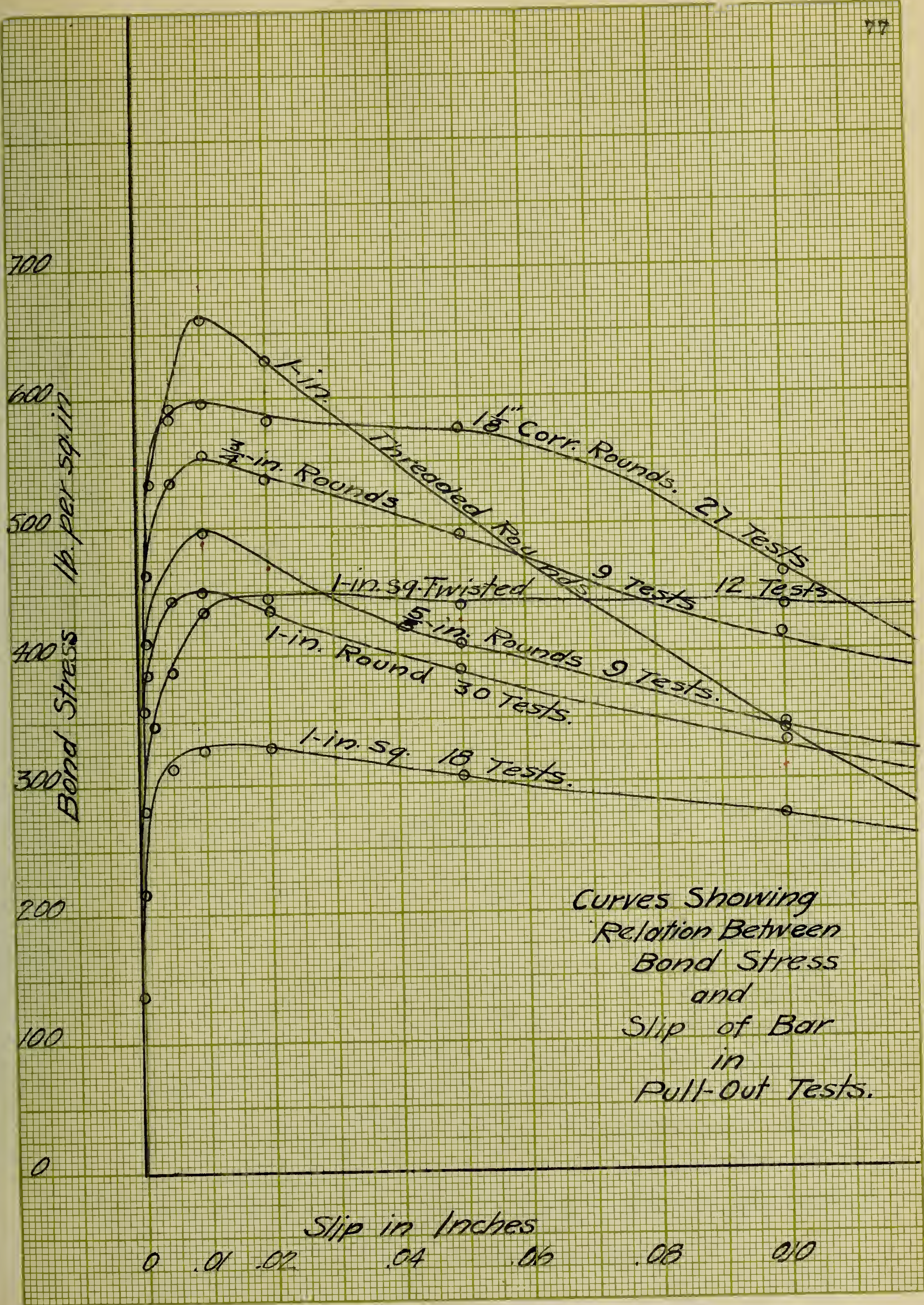
17. The test Beam No. 1055.8 reinforced with 1-in. plain round bar shows that a bond stress of about 200 lb. per sq. in. probably would not cause failure of the beams if this stress were continued indefinitely.

18. The beams were designed to develop high bond stress, but 100 and 120 lb. per sq. in. for plain and corrugated bars will, under favorable conditions, give a sufficient factor of safety.

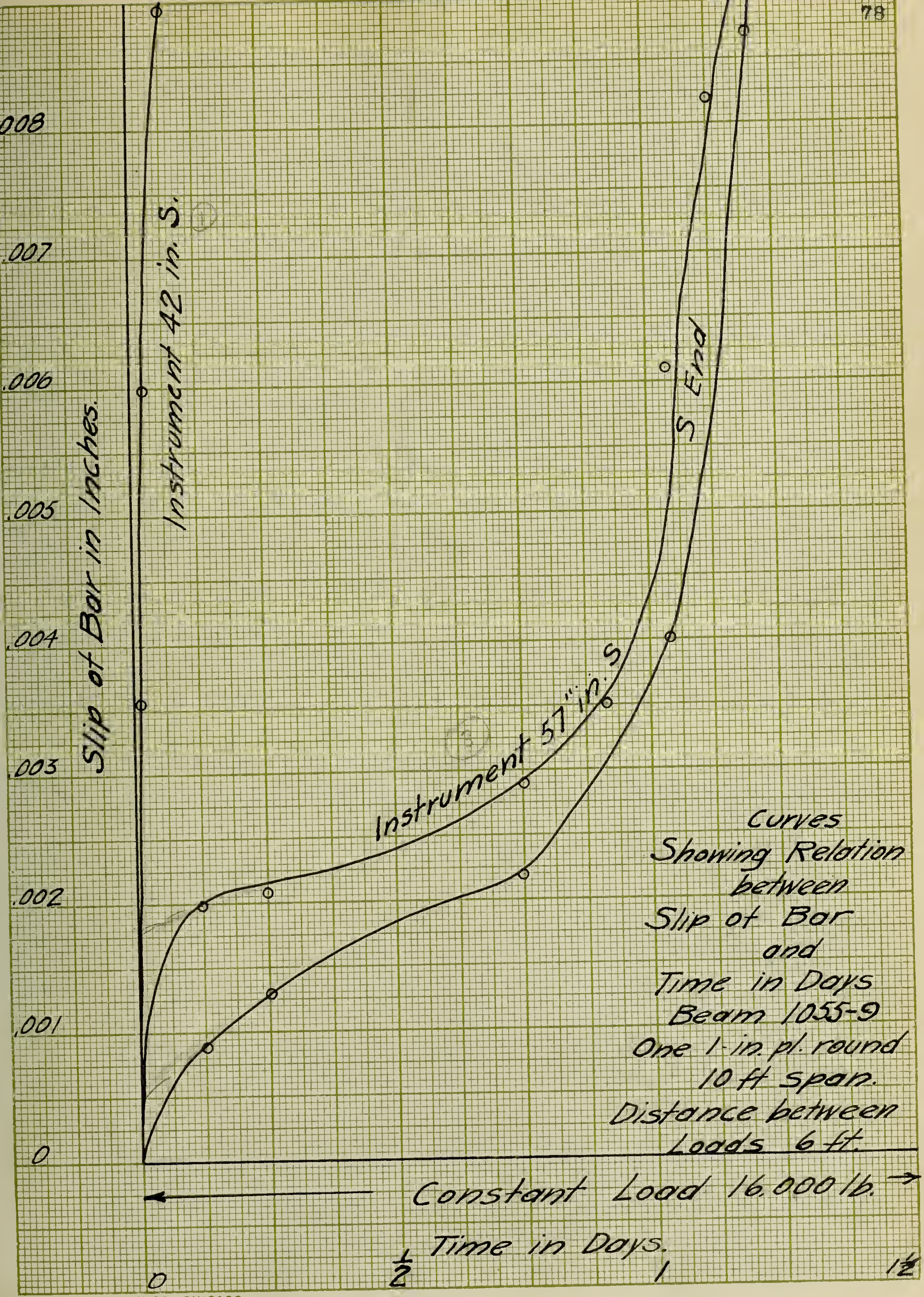


Curves
Showing Relation
Between Bond Stress
and
Tangent α
6-ft. Beams.
Distance between loads
2, 2½, 3, 3½ and 4-ft.

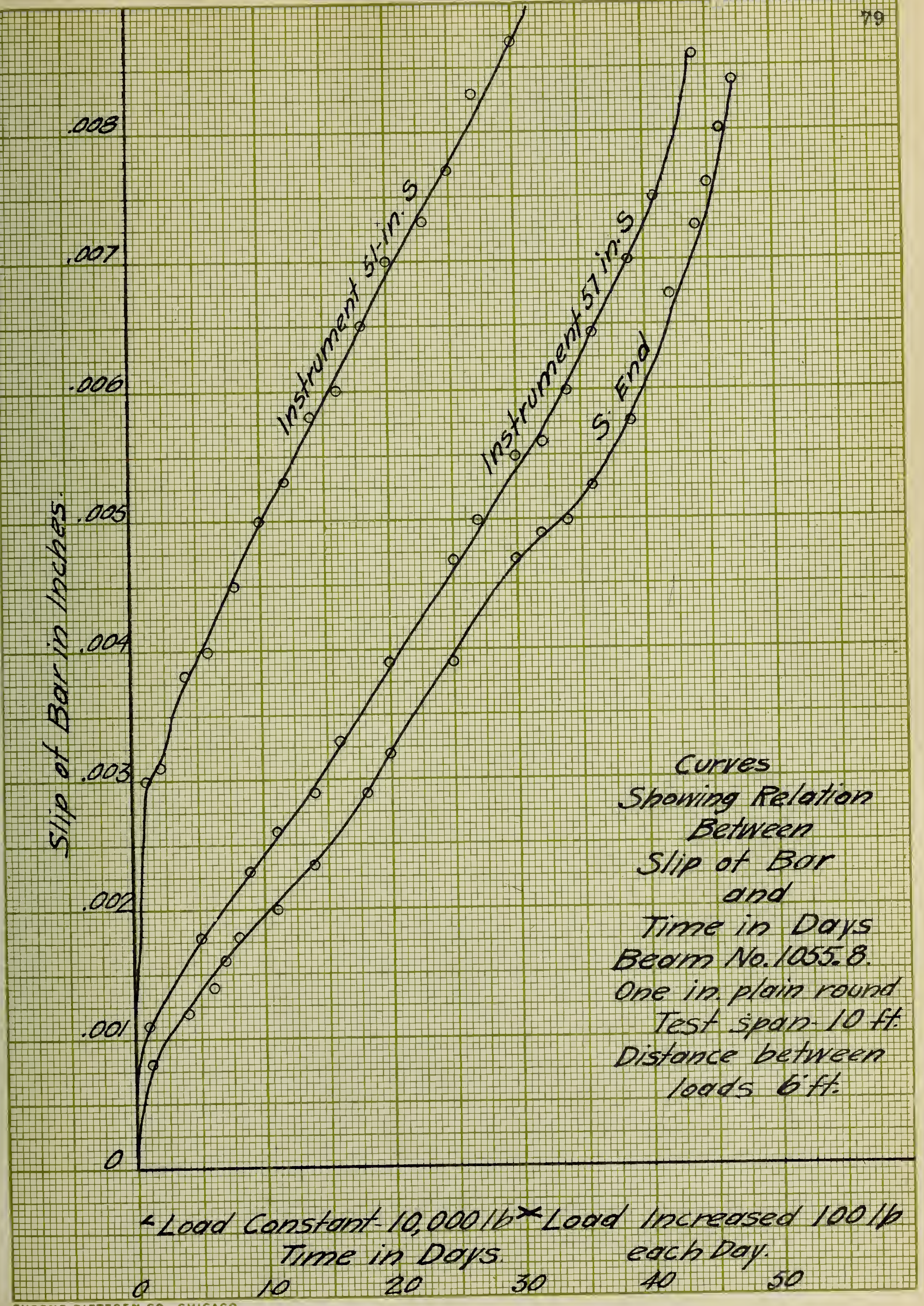

Percent of Maximum Bond Stress.
100
80
60
40
20
0
Machine $\frac{3}{4}$-in round
Machine $\frac{5}{8}$-in round
Machine 1-in. sq.
Hand $\frac{3}{4}$-in pl. round
Hand $\frac{5}{8}$-in
Hand $1\frac{1}{8}$ corr round
Hand 1-in. Threaded
Machine $1\frac{1}{8}$-in. Corr. round
Machine 1-in. Threaded
Hand 1-in. sq. Twisted
Machine sq. Twisted
Curves
Showing Relation
between
Percent of Max. Bond Stress
and
Slip of Bar in
Pull-out Tests
Slip of Bar in Inches.
0
.001
.002
.003
.004
.005



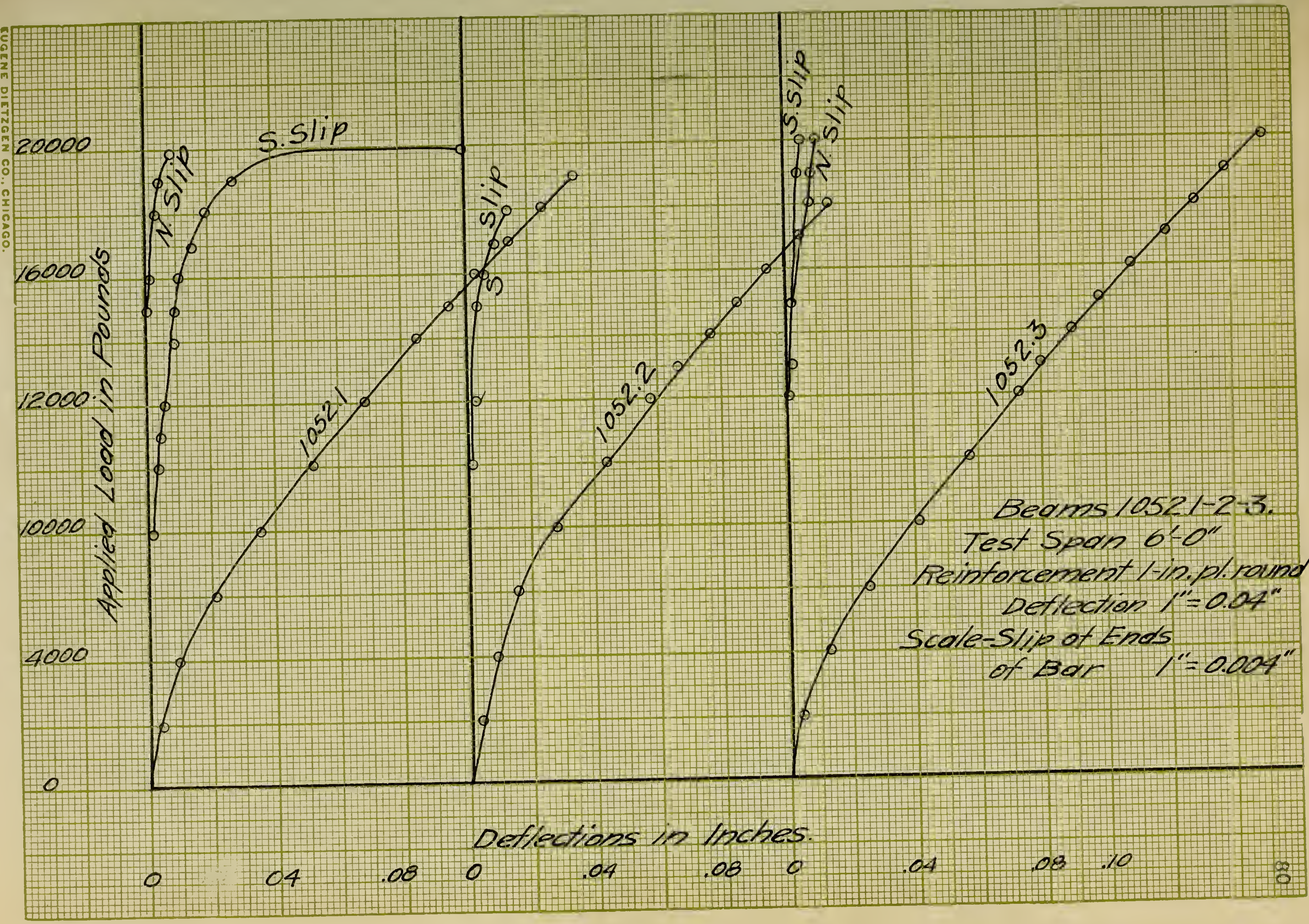
700
600
500
400
300
200
100
0
Bond Stress lb. per sq. in.
1-in. Threaded Rounds 9 Tests
1 1/8" Corr. Rounds. 27 Tests
3/4-in. Rounds 12 Tests
1-in. sq. Twisted
5/8-in. Rounds 9 Tests.
1-in. Round 30 Tests.
1-in. sq. 18 Tests.
Curves Showing Relation Between Bond Stress and Slip of Bar in Pull-Out Tests.
Slip in Inches
0
.01
.02
.04
.06
.08
0.10

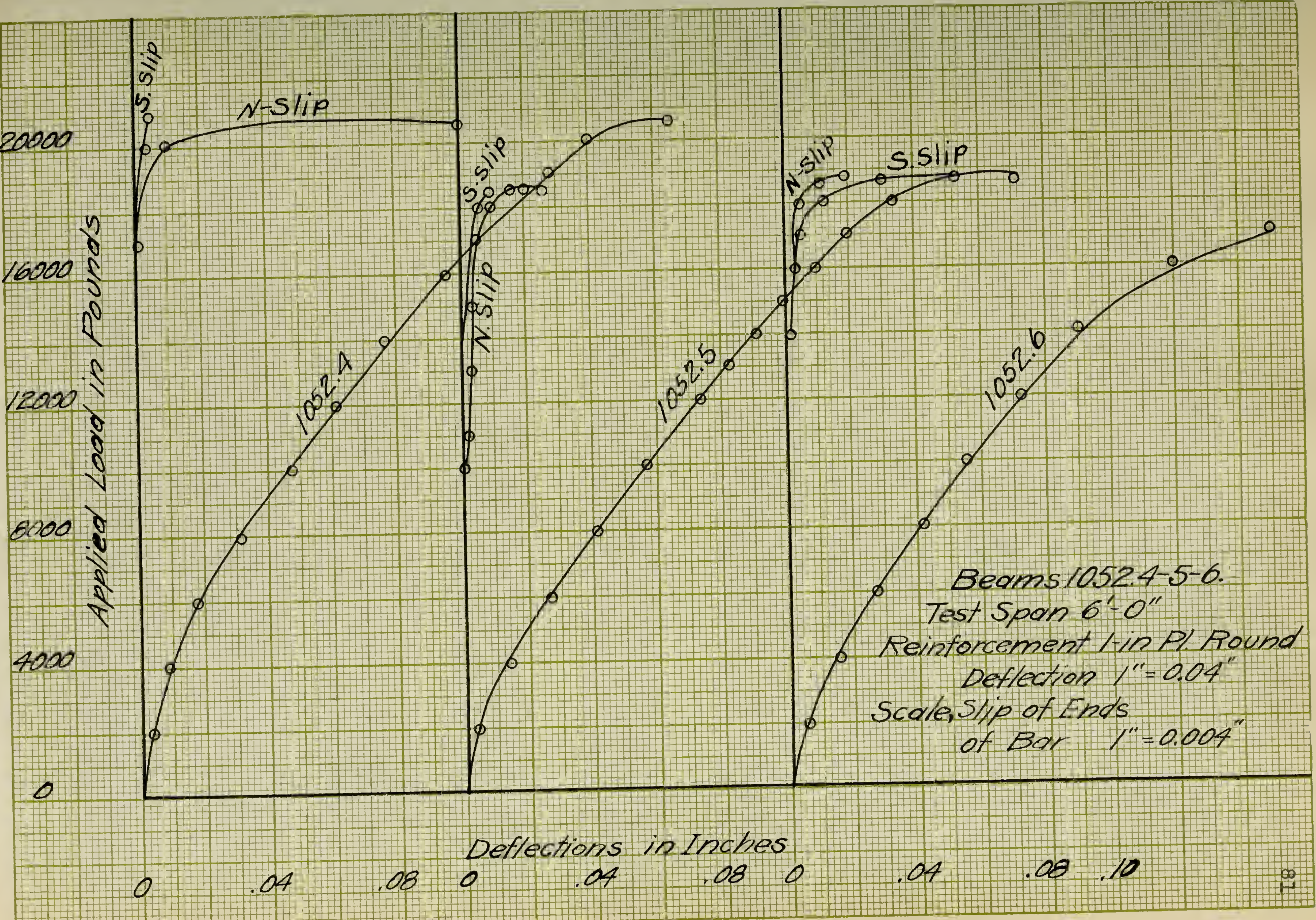


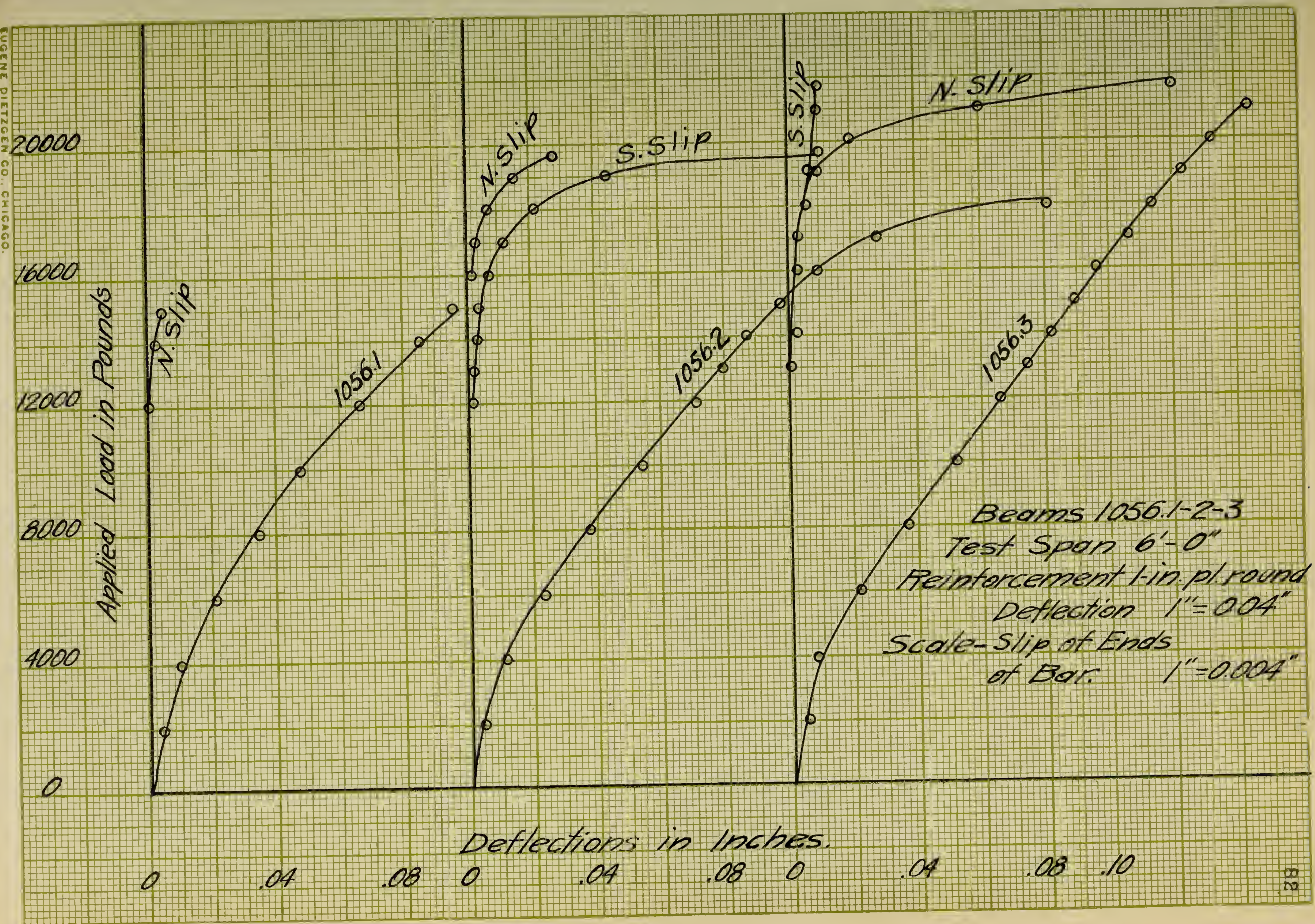
.008
.007
.006
.005
.004
.003
.002
.001
0
Slip of Bar in Inches.
Instrument 42 in. S.
Instrument 57" in. S
S End
Curves
Showing Relation
between
Slip of Bar
and
Time in Days
Beam 1055-9
One 1-in. pl. round
10 ft span.
Distance between
Loads 6 ft.
Constant Load 16,000 lb.
Time in Days.
0
½
1
1½



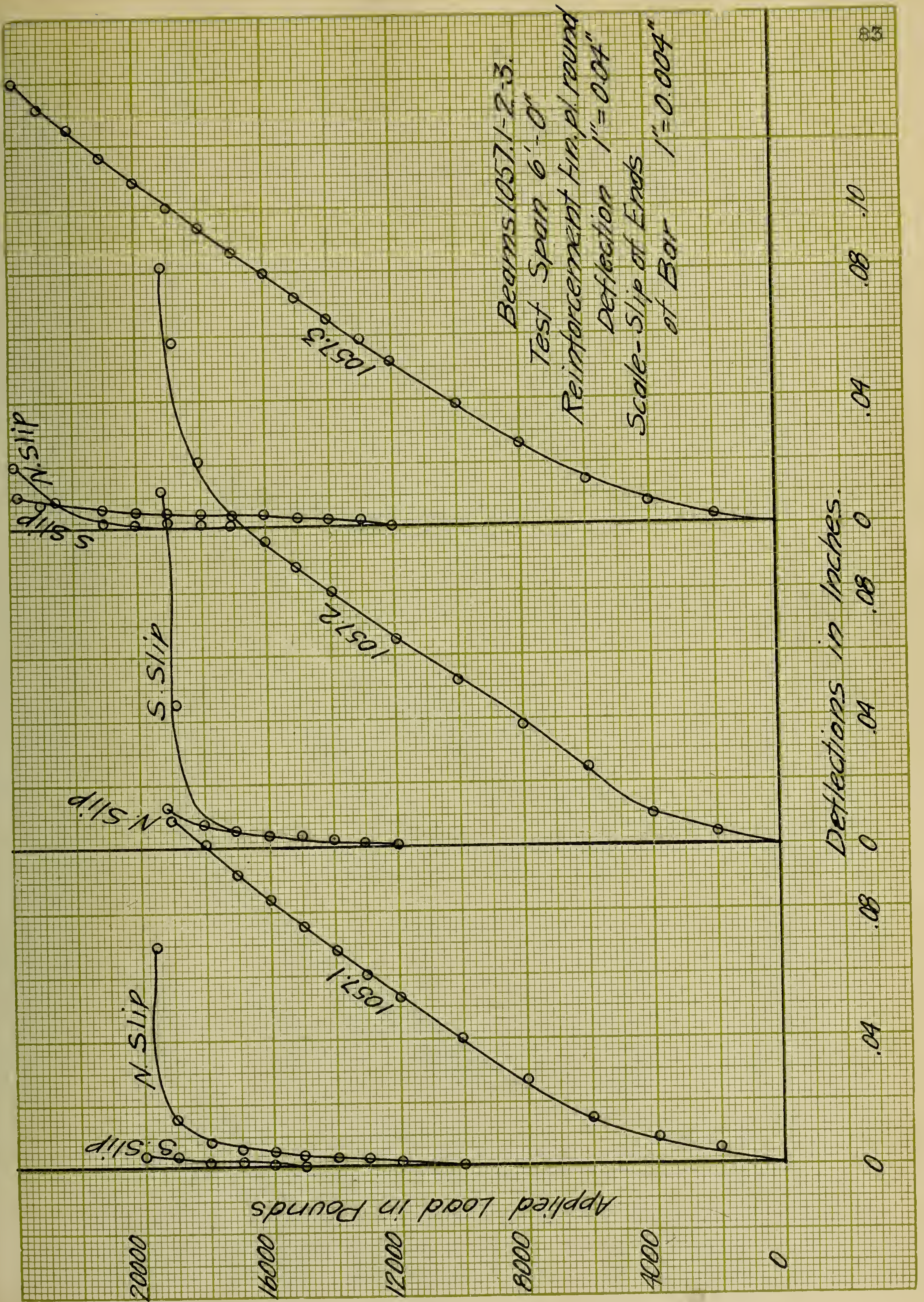
Curves
Showing Relation
Between
Slip of Bar
and
Time in Days
Beam No. 1055.8.
One in. plain round
Test span-10 ft.
Distance between
loads 6 ft.
Instrument 51-in. S
Instrument 57 in. S
S. End
Slip of Bar in Inches.
.008
.007
.006
.005
.004
.003
.002
.001
0
←Load Constant-10,000 lb ×Load Increased 100 lb each Day.
Time in Days.
0
10
20
30
40
50

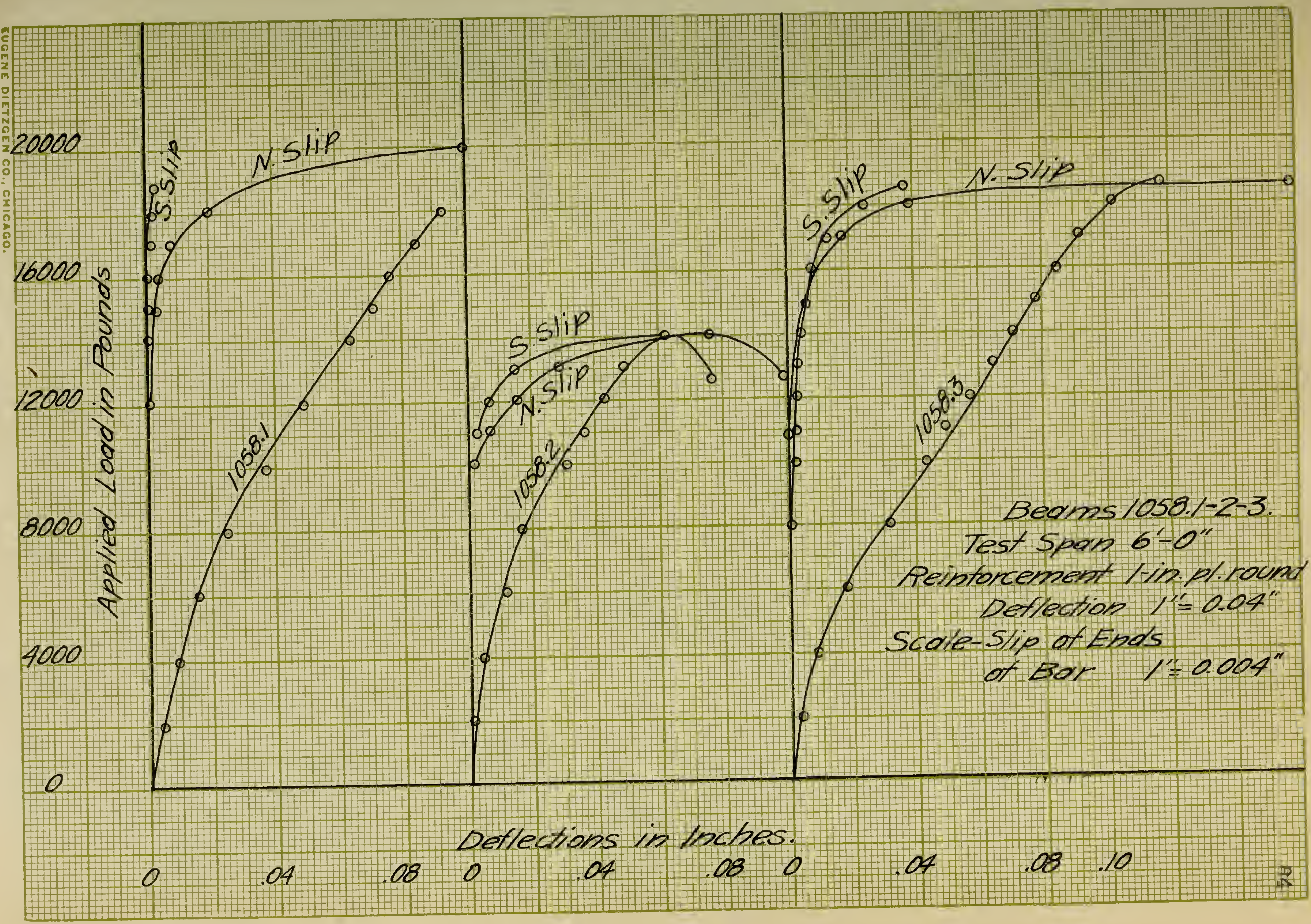

Beams 1052.1-2-3.
Test Span 6'-0"
Reinforcement 1-in. pl. round
Deflection 1" = 0.04"
Scale-Slip of Ends
of Bar 1" = 0.004"
Applied Load in Pounds
Deflections in Inches.
1052.1
1052.2
1052.3
S. Slip
N. Slip
Slip
S
20000
16000
12000
10000
4000
0
.04
.08
.10

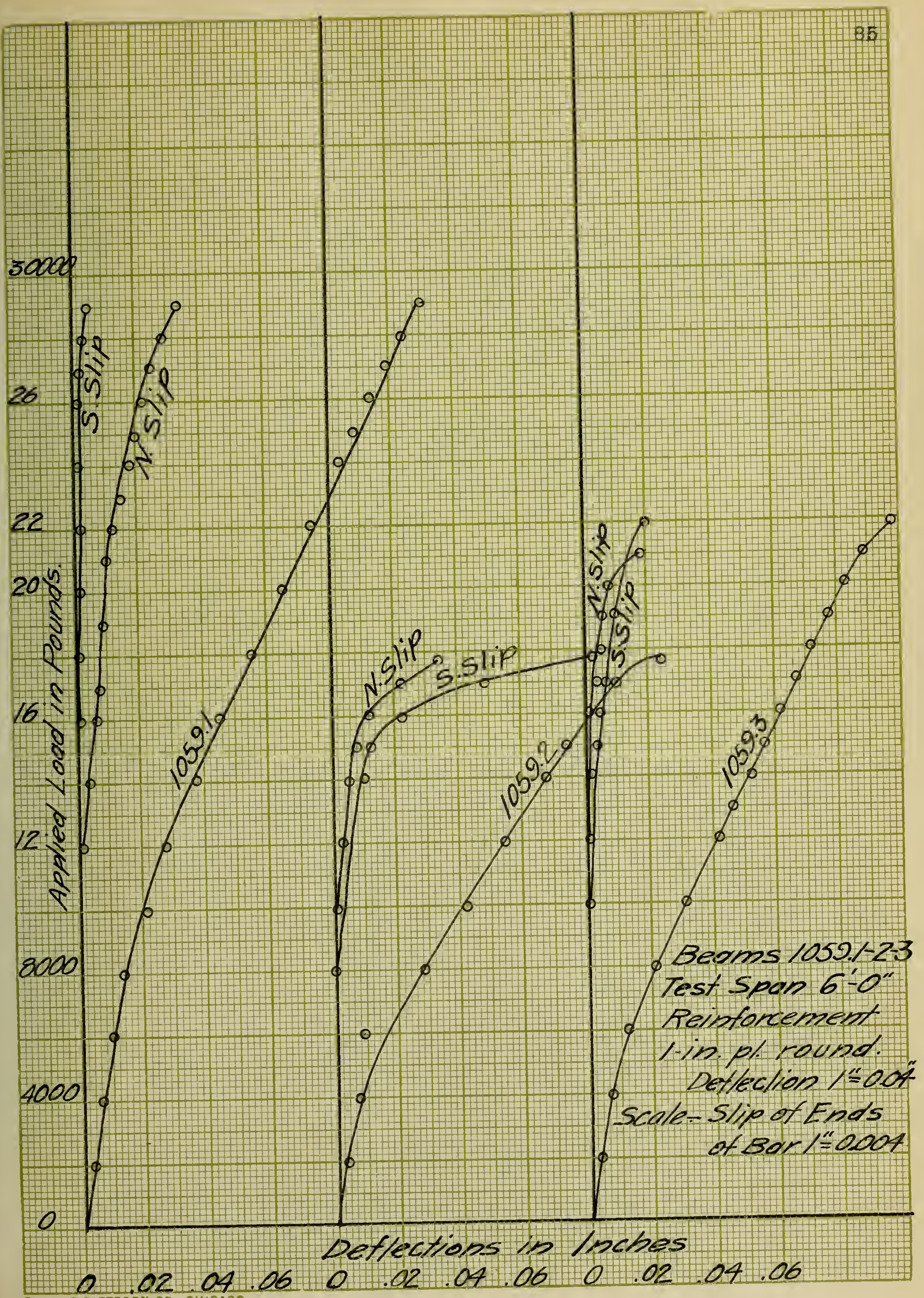

Beams 1052.4-5-6.
Test Span 6'-0"
Reinforcement 1-in Pl. Round
Deflection 1" = 0.04"
Scale, Slip of Ends
of Bar 1" = 0.004"
1052.4
1052.5
1052.6
N-Slip
S. Slip
Applied Load in Pounds
Deflections in Inches
0
4000
8000
12000
16000
20000
0
.04
.08
.10

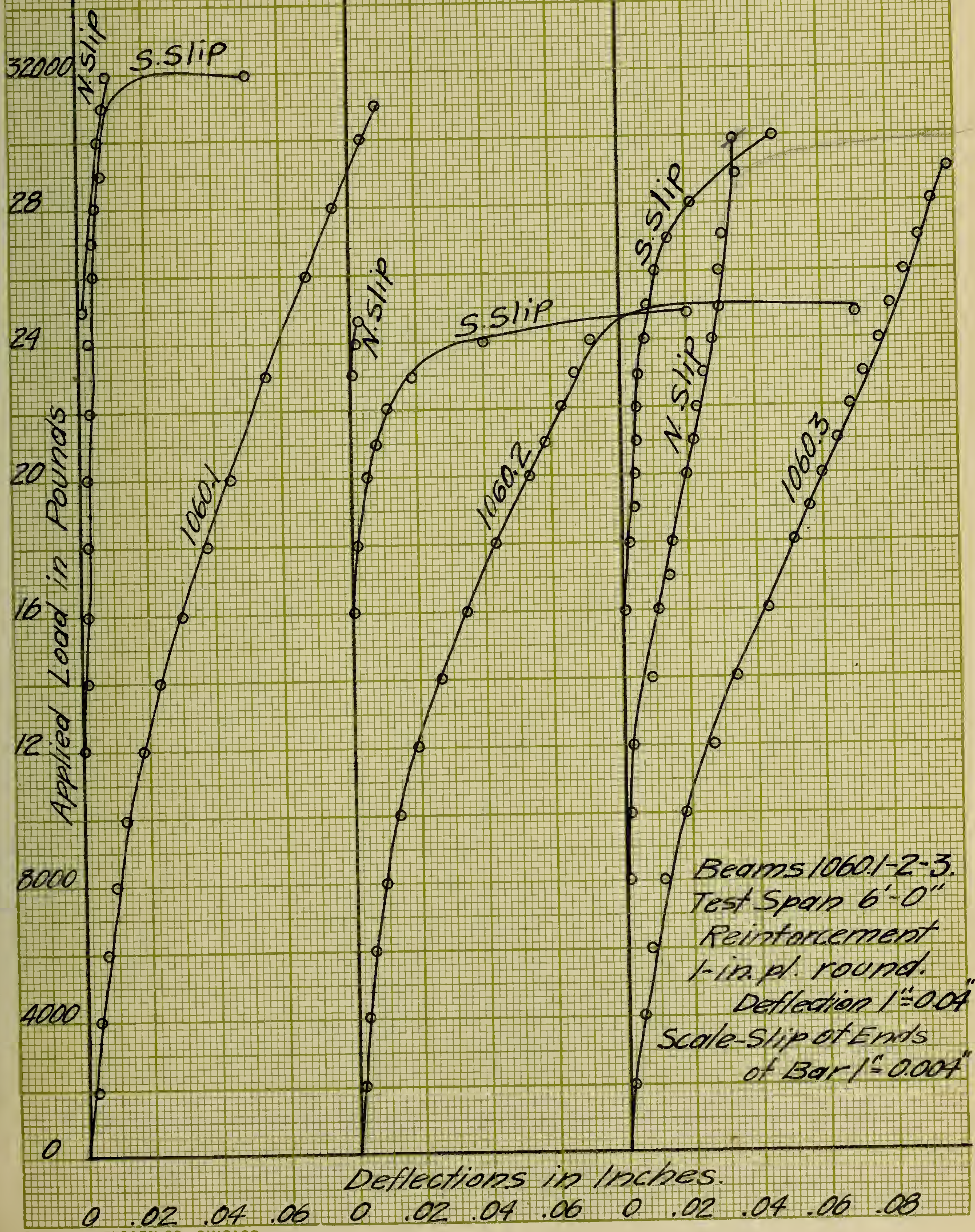


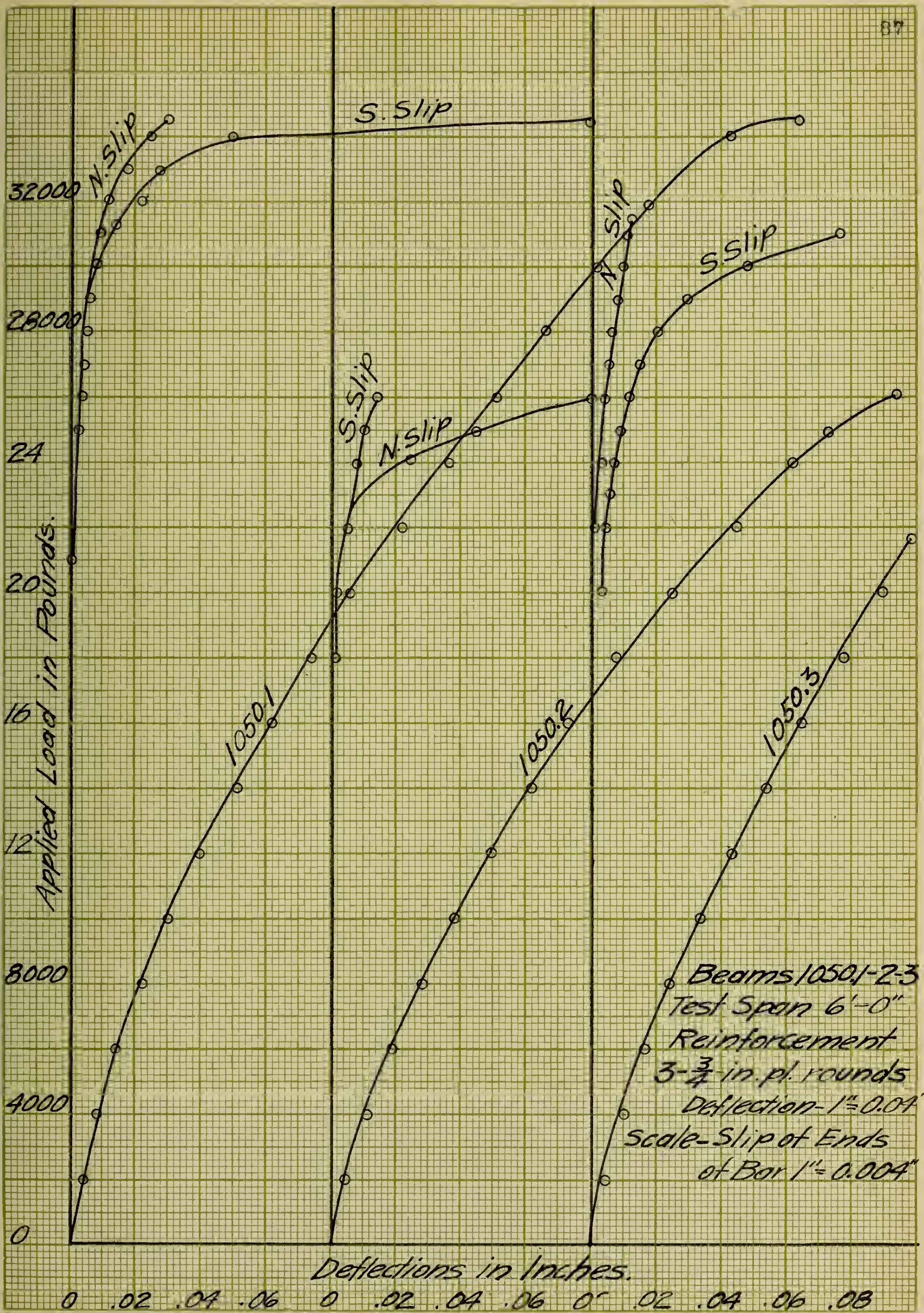
Beams 1056.1-2-3
Test Span 6'-0"
Reinforcement 1-in. pl. round
Deflection 1"=0.04"
Scale - Slip of Ends of Bar. 1"=0.004"
Applied Load in Pounds
0
4000
8000
12000
16000
20000
Deflections in Inches.
0
.04
.08
0
.04
.08
0
.04
.08
.10
1056.1
1056.2
1056.3
N. Slip
N. Slip
S. Slip
S. Slip
N. Slip


Beams 1057.1-2-3.
Test Span 6'-0"
Reinforcement 1 in. pl. round
Deflection 1" = 0.04"
Scale - Slip of Ends of Bar 1" = 0.004"
1057.3
1057.2
1057.1
N. Slip
S. Slip
Deflections in Inches.
Applied Load in Pounds
0
.04
.08
.10
4000
8000
12000
16000
20000


Beams 1058.1-2-3.
Test Span 6'-0"
Reinforcement 1-in. pl. round
Deflection 1" = 0.04"
Scale-Slip of Ends of Bar 1" = 0.004"
Applied Load in Pounds
Deflections in Inches.
20000
16000
12000
8000
4000
0
0
.04
.08
0
.04
.08
0
.04
.08
.10
N. Slip
S. Slip
1058.1
S. Slip
N. Slip
1058.2
S. Slip
N. Slip
1058.3
84


30000
26
22
20
16
12
8000
4000
0
Applied Load in Pounds.
S. Slip
N. Slip
1059.1
N. Slip
S. Slip
1059.2
N. Slip
S. Slip
1059.3
Beams 1059.1-2-3
Test Span 6'-0"
Reinforcement
1-in. pl. round.
Deflection 1"=0.04"
Scale - Slip of Ends
of Bar 1"=0.004
Deflections in Inches
0 .02 .04 .06 0 .02 .04 .06 0 .02 .04 .06


N. Slip
S. Slip
32000
28
24
20
16
12
8000
4000
0
Applied Load in Pounds
1060.1
N. Slip
S. Slip
1060.2
S. Slip
N. Slip
1060.3
Beams 1060.1-2-3.
Test Span 6'-0"
Reinforcement
1-in. pl. round.
Deflection 1"=0.04"
Scale-Slip at Ends
of Bar 1"=0.004"
Deflections in Inches.
0 .02 .04 .06 0 .02 .04 .06 0 .02 .04 .06 .08



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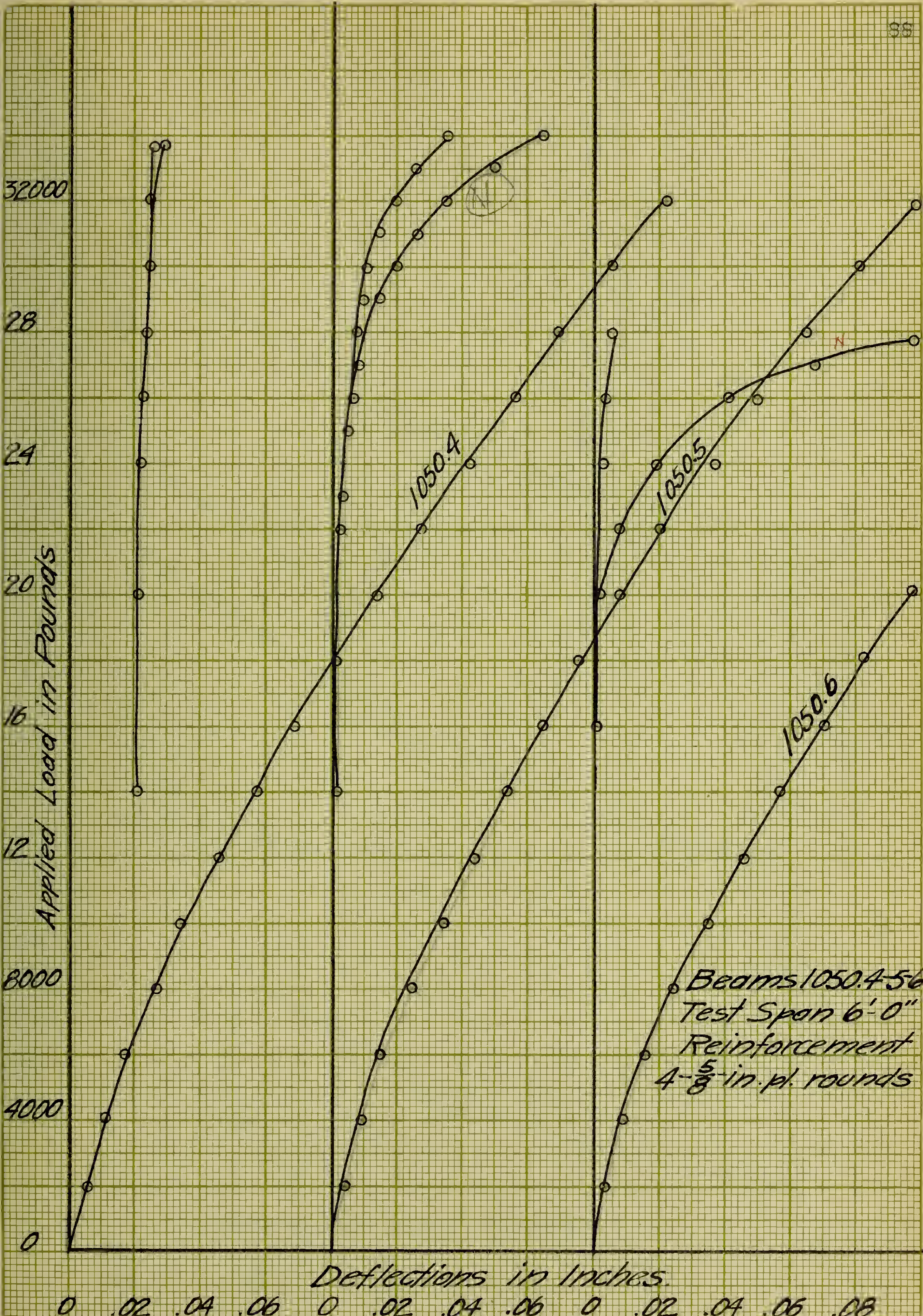
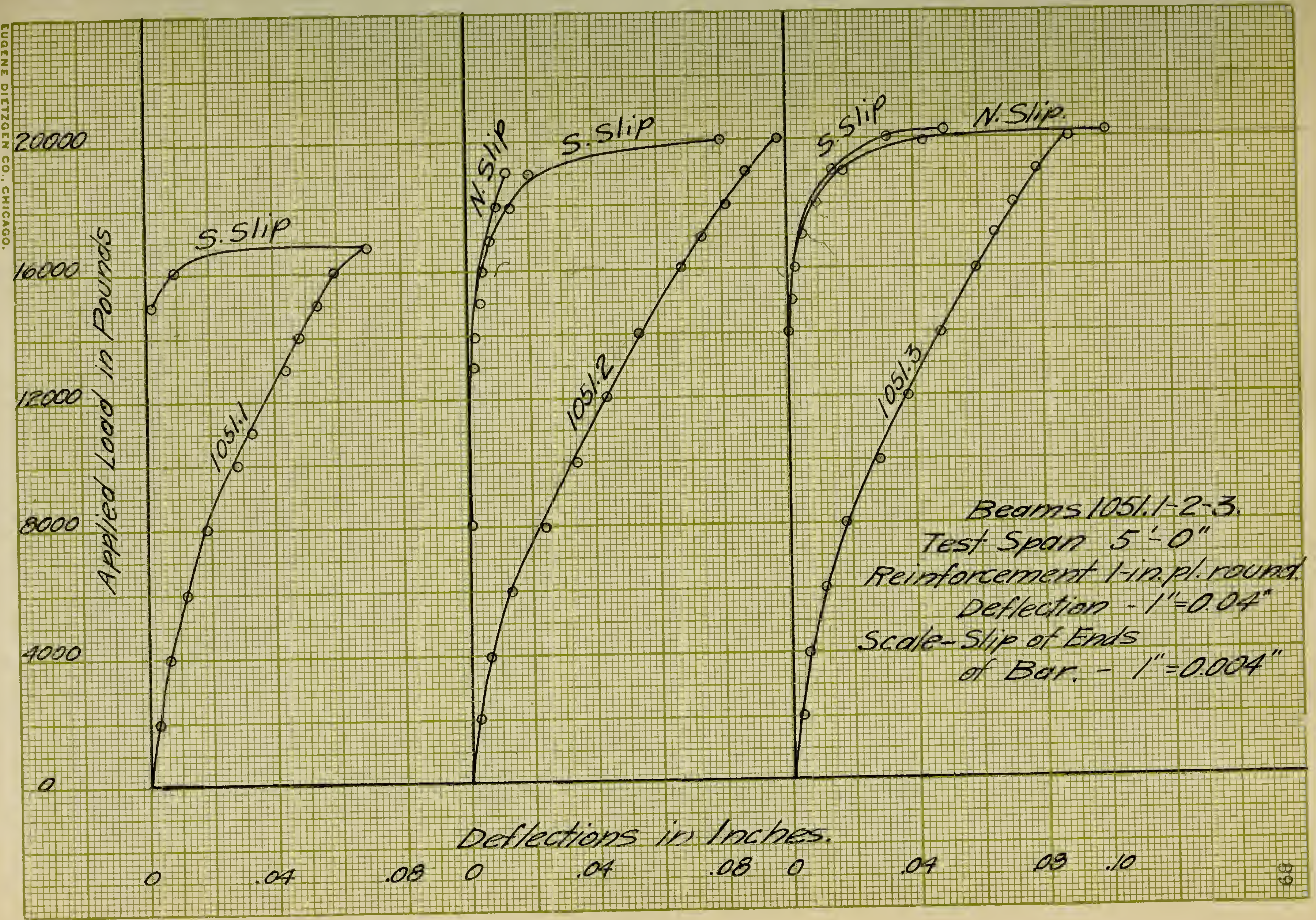
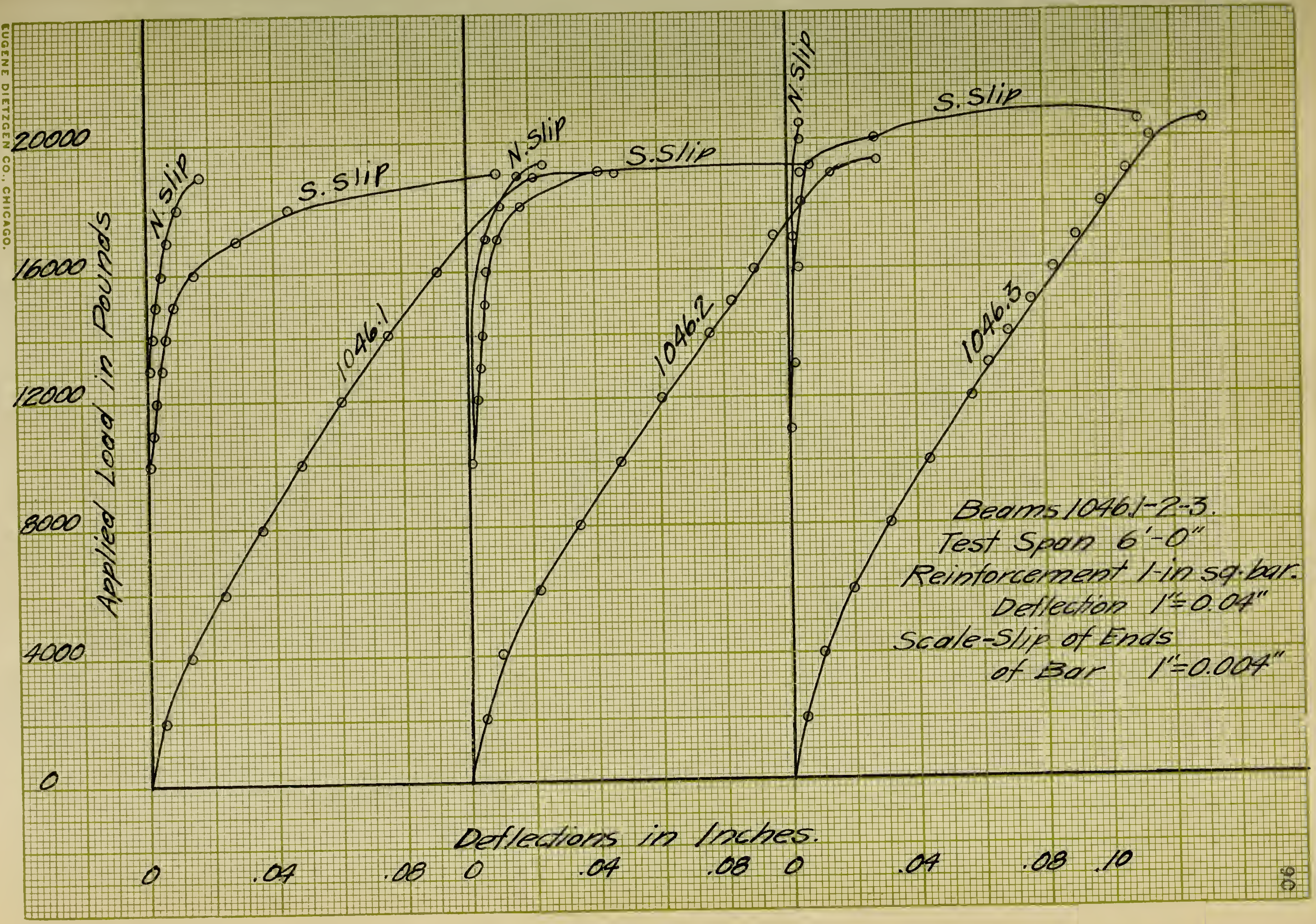


86
Applied Load in Pounds
32000
28
24
20
16
12
8000
4000
0
1050.4
1050.5
1050.6
Beams 1050.4-5-6
Test Span 6'-0"
Reinforcement
4-5/8-in. pl. rounds
Deflections in Inches.
0
.02
.04
.06
0
.02
.04
.06
0
.02
.04
.06
.08



Beams 1051.1-2-3.
Test Span 5'-0"
Reinforcement 1-in. pl. round.
Deflection - 1"=0.04"
Scale-Slip of Ends of Bar. - 1"=0.004"
Applied Load in Pounds
Deflections in Inches.
S. Slip
N. Slip
1051.1
1051.2
1051.3
0
4000
8000
12000
16000
20000
.04
.08
.10


Beams 1046.1-2-3.
Test Span 6'-0"
Reinforcement 1-in sq. bar.
Deflection 1"=0.04"
Scale-Slip of Ends
of Bar 1"=0.004"
Applied Load in Pounds
20000
16000
12000
8000
4000
0
Deflections in Inches.
0
.04
.08
0
.04
.08
0
.04
.08
.10
1046.1
1046.2
1046.3
N. slip
S. slip
N. Slip
S. Slip
N. Slip
S. Slip
96
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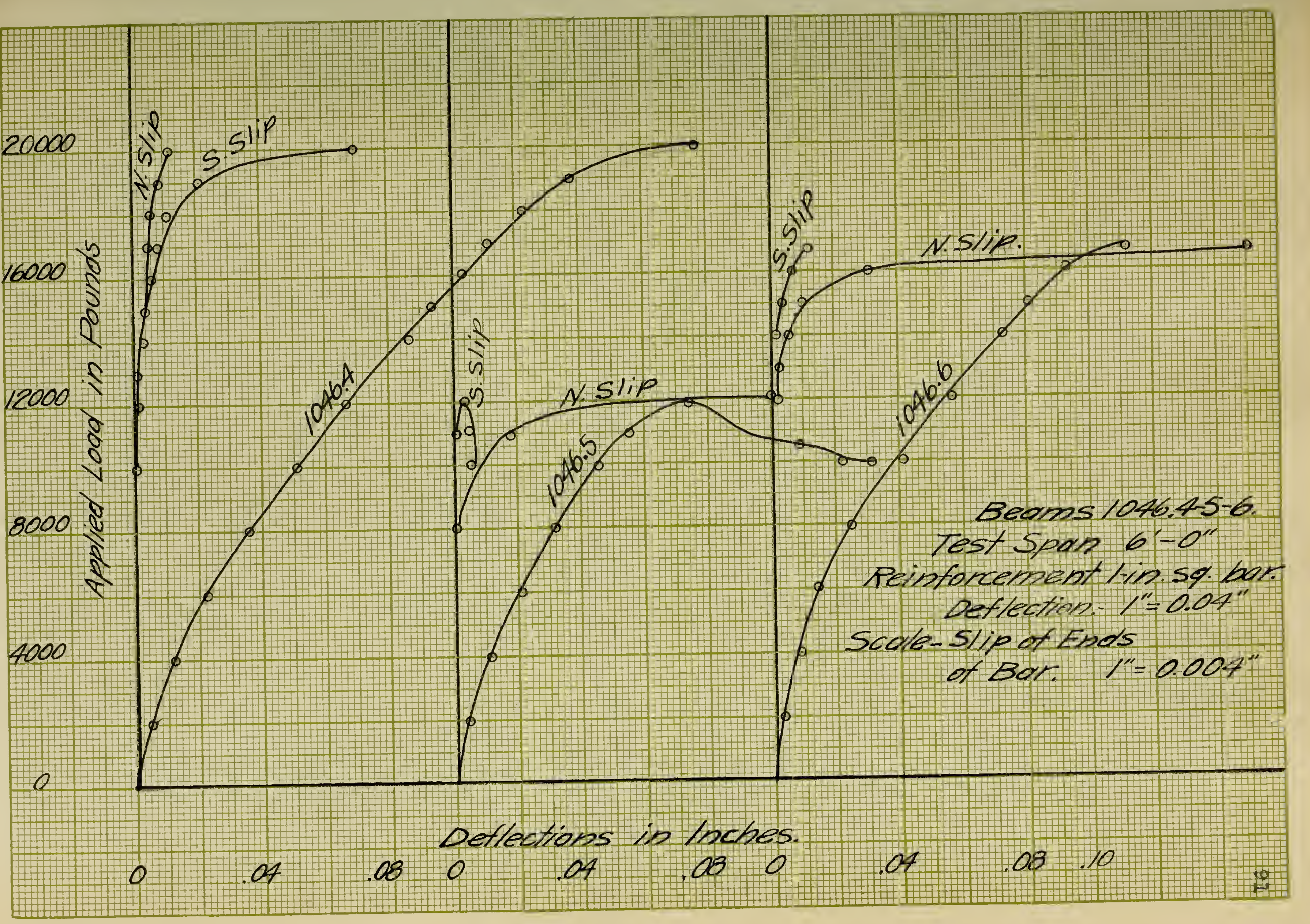
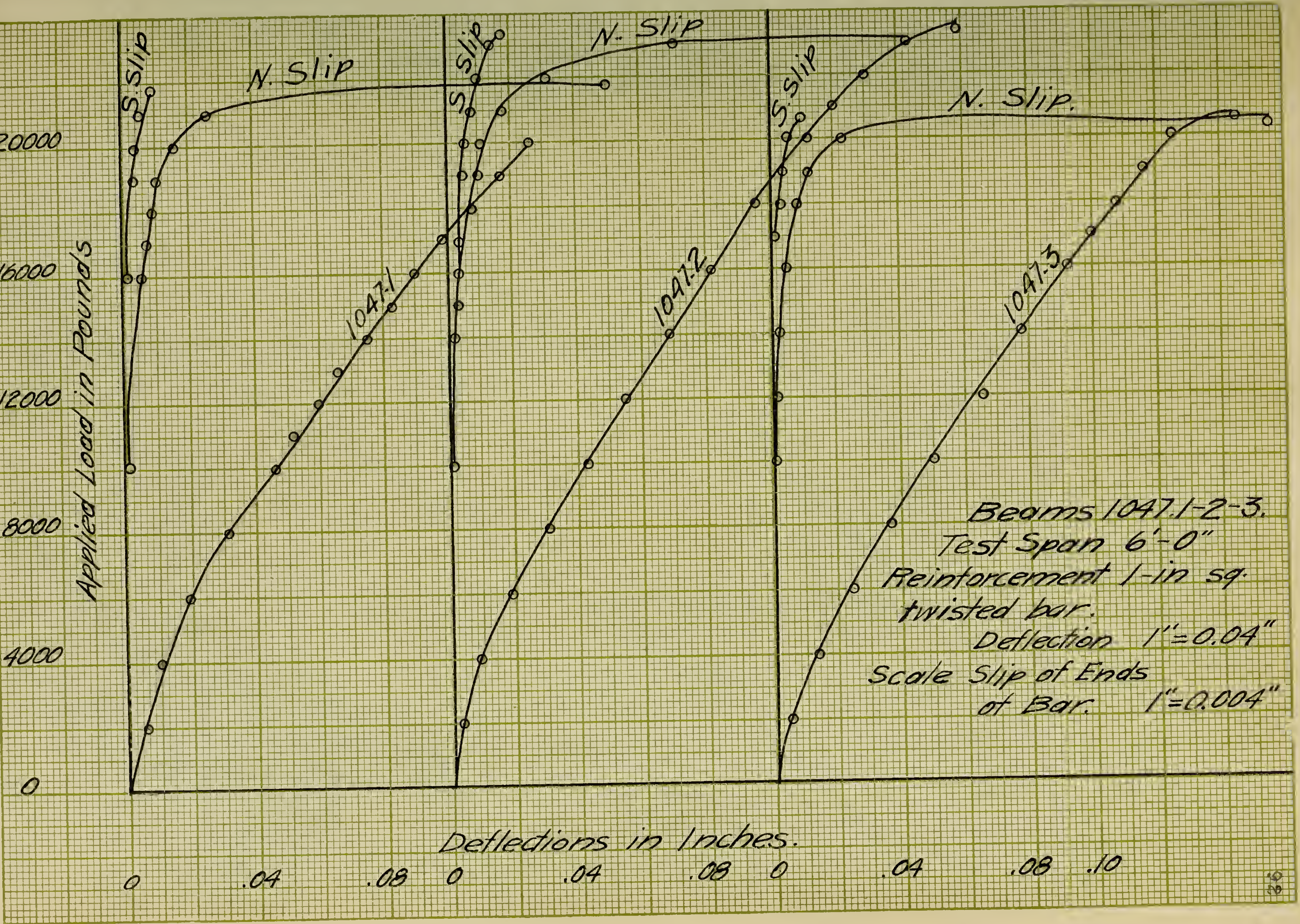
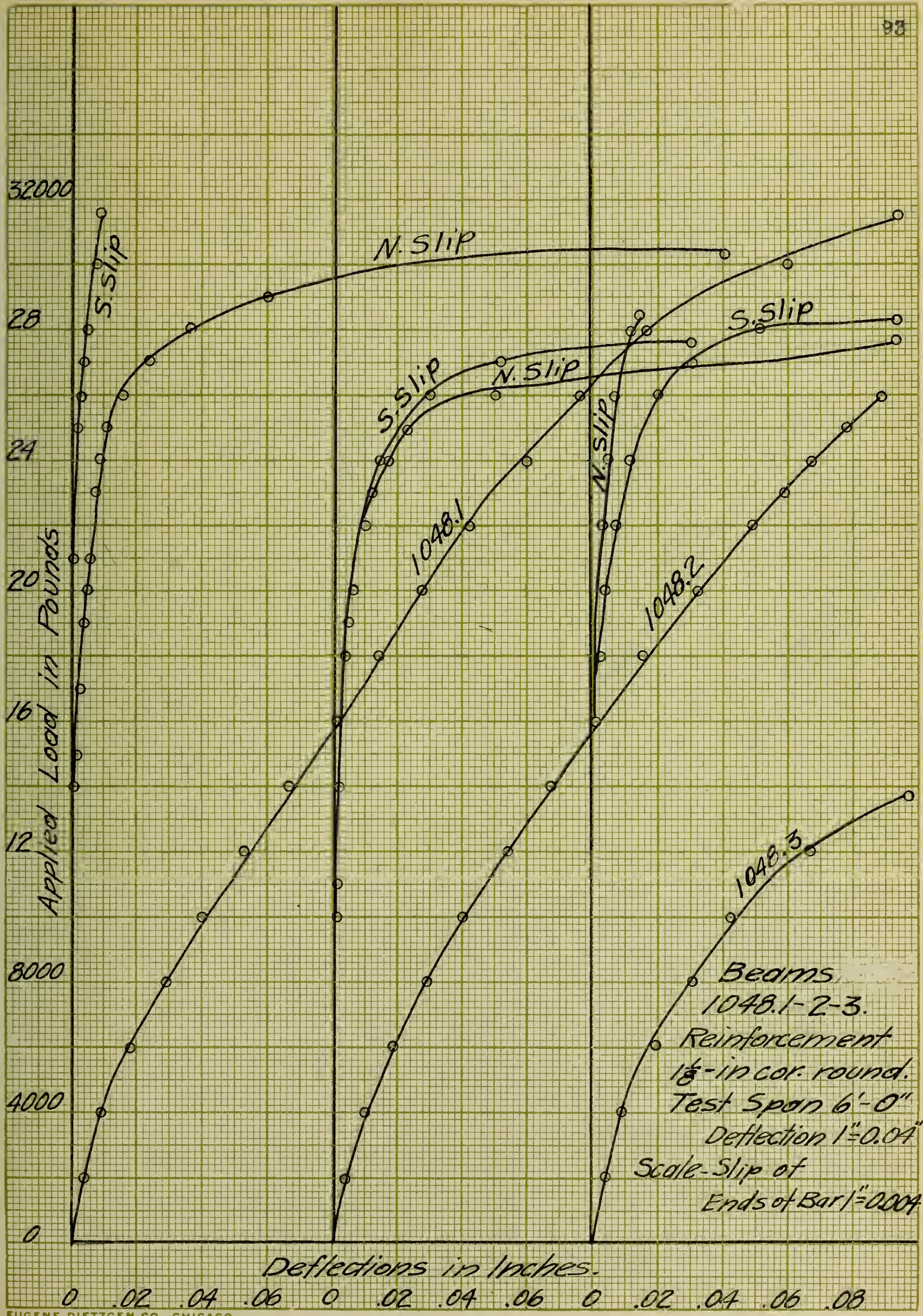
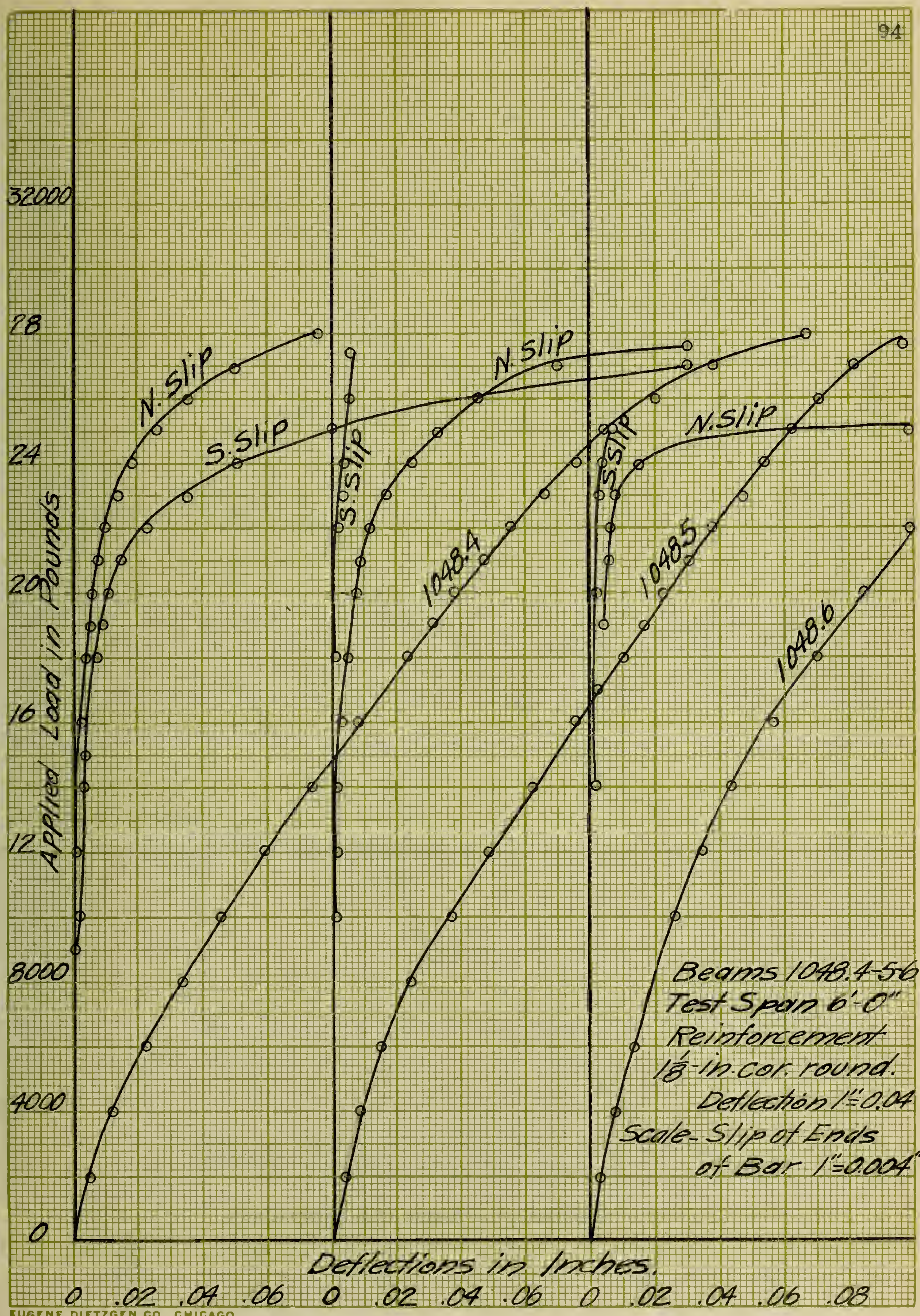
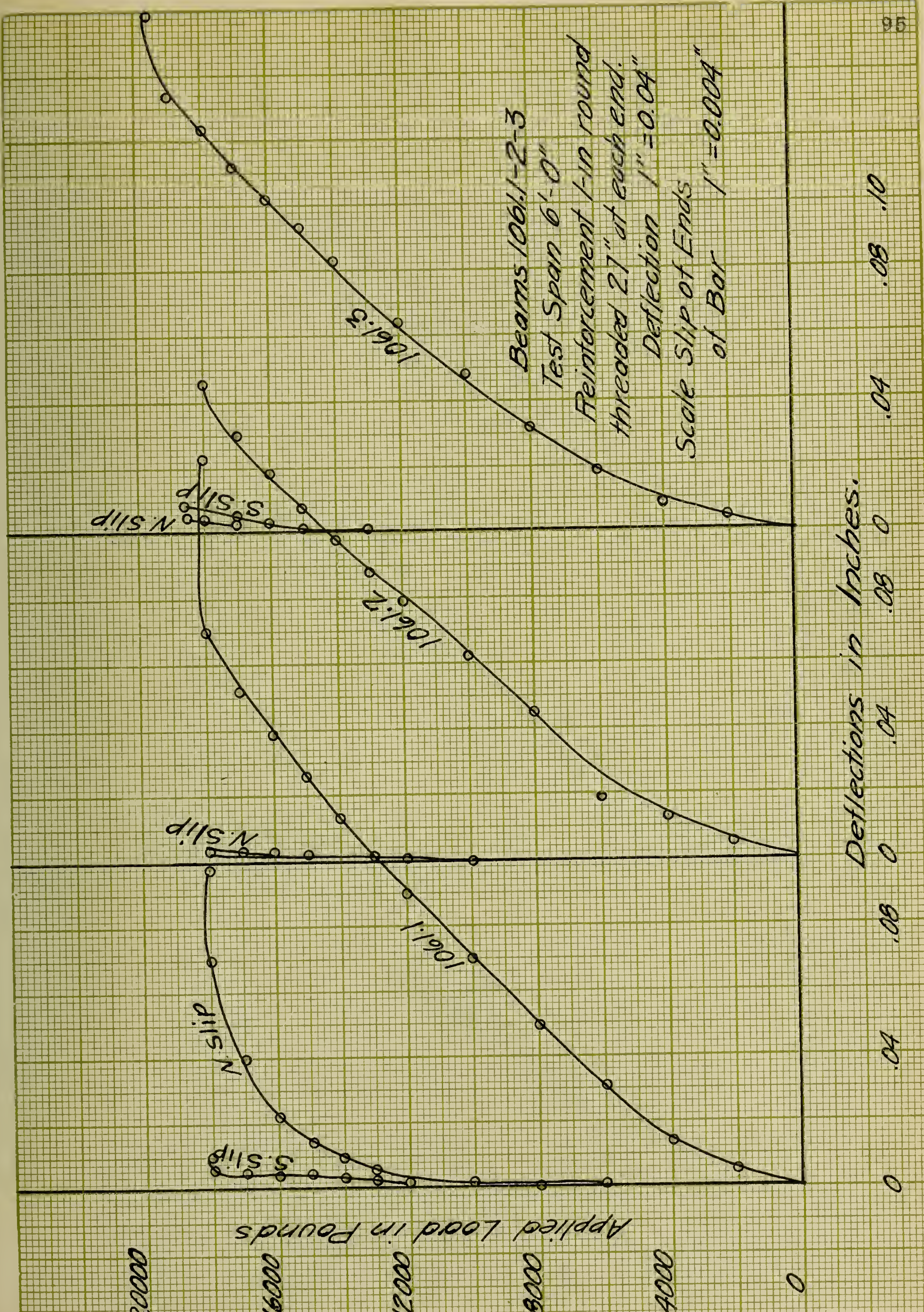
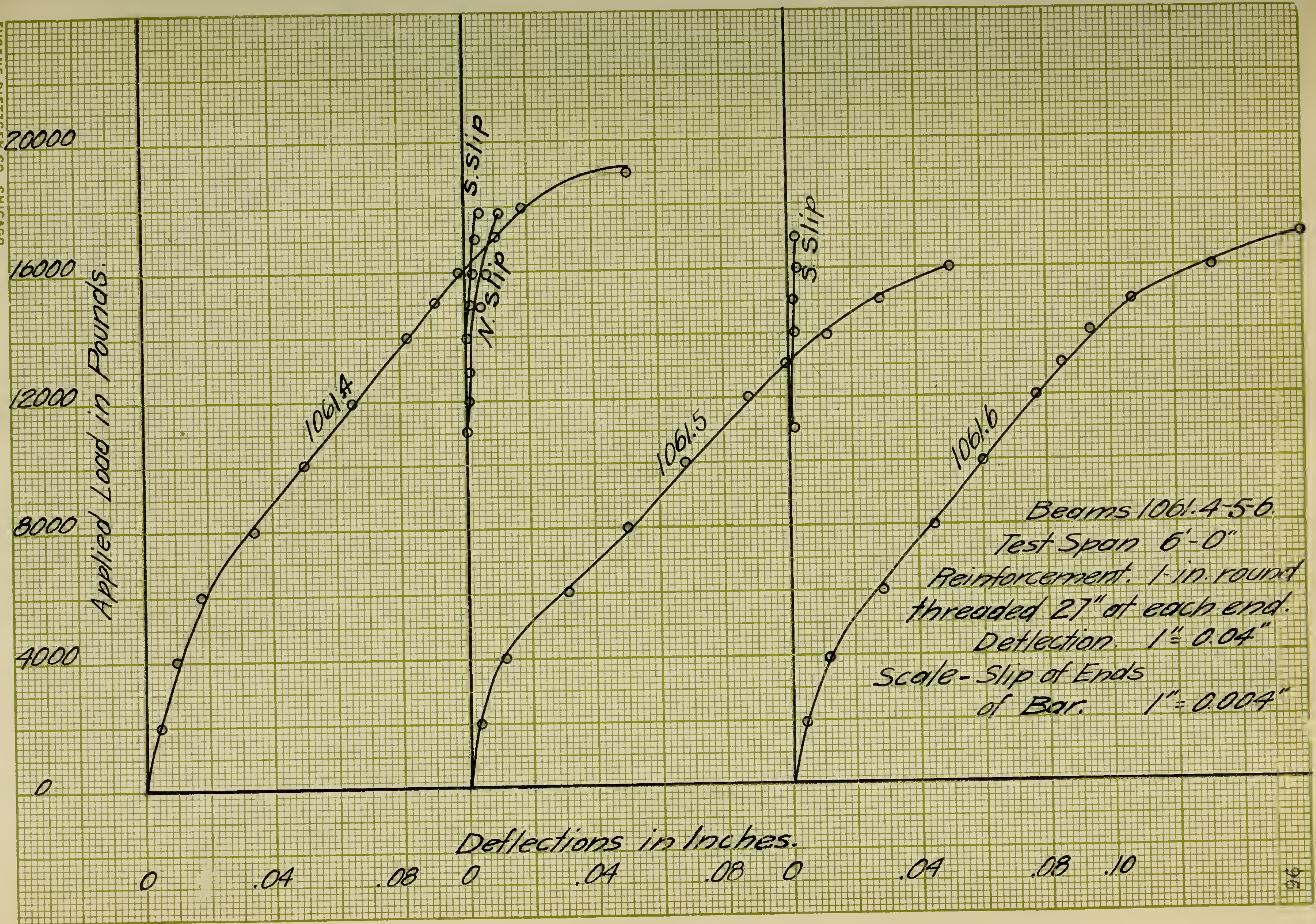

Beams 1046.4-5-6.
Test Span 6'-0"
Reinforcement 1-in. sq. bar.
Deflection:- 1" = 0.04"
Scale-Slip of Ends
of Bar. 1" = 0.004"
Applied Load in Pounds
Deflections in Inches.
1046.4
1046.5
1046.6
N. Slip
S. Slip
0
4000
8000
12000
16000
20000
0
.04
.08

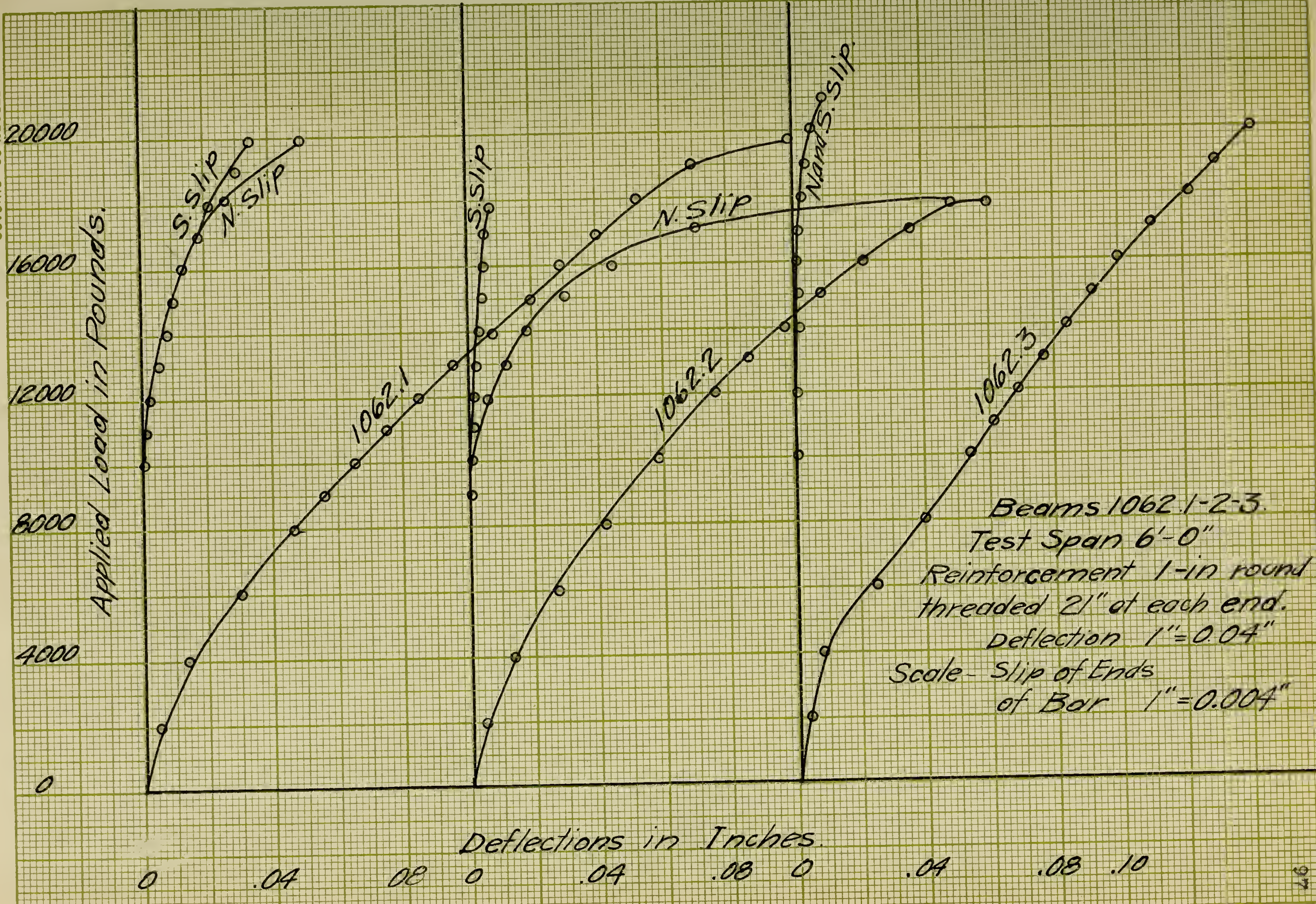

Beams 1047.1-2-3.
Test Span 6'-0"
Reinforcement 1-in sq. twisted bar.
Deflection 1"=0.04"
Scale Slip of Ends of Bar. 1"=0.004"
Applied Load in Pounds
Deflections in Inches.
1047.1
1047.2
1047.3
N. Slip
S. Slip
0
4000
8000
12000
16000
20000
.04
.08
.10


32000
28
24
20
16
12
8000
4000
0
Applied Load in Pounds
S. Slip
N. Slip
S. Slip
N. Slip
1048.1
N. Slip
S. Slip
1048.2
1048.3
Beams
1048.1-2-3.
Reinforcement
1⅛-in cor. round.
Test Span 6'-0"
Deflection 1"=0.04"
Scale-Slip of
Ends of Bar 1"=0.004"
Deflections in Inches.
0
.02
.04
.06
0
.02
.04
.06
0
.02
.04
.06
.08

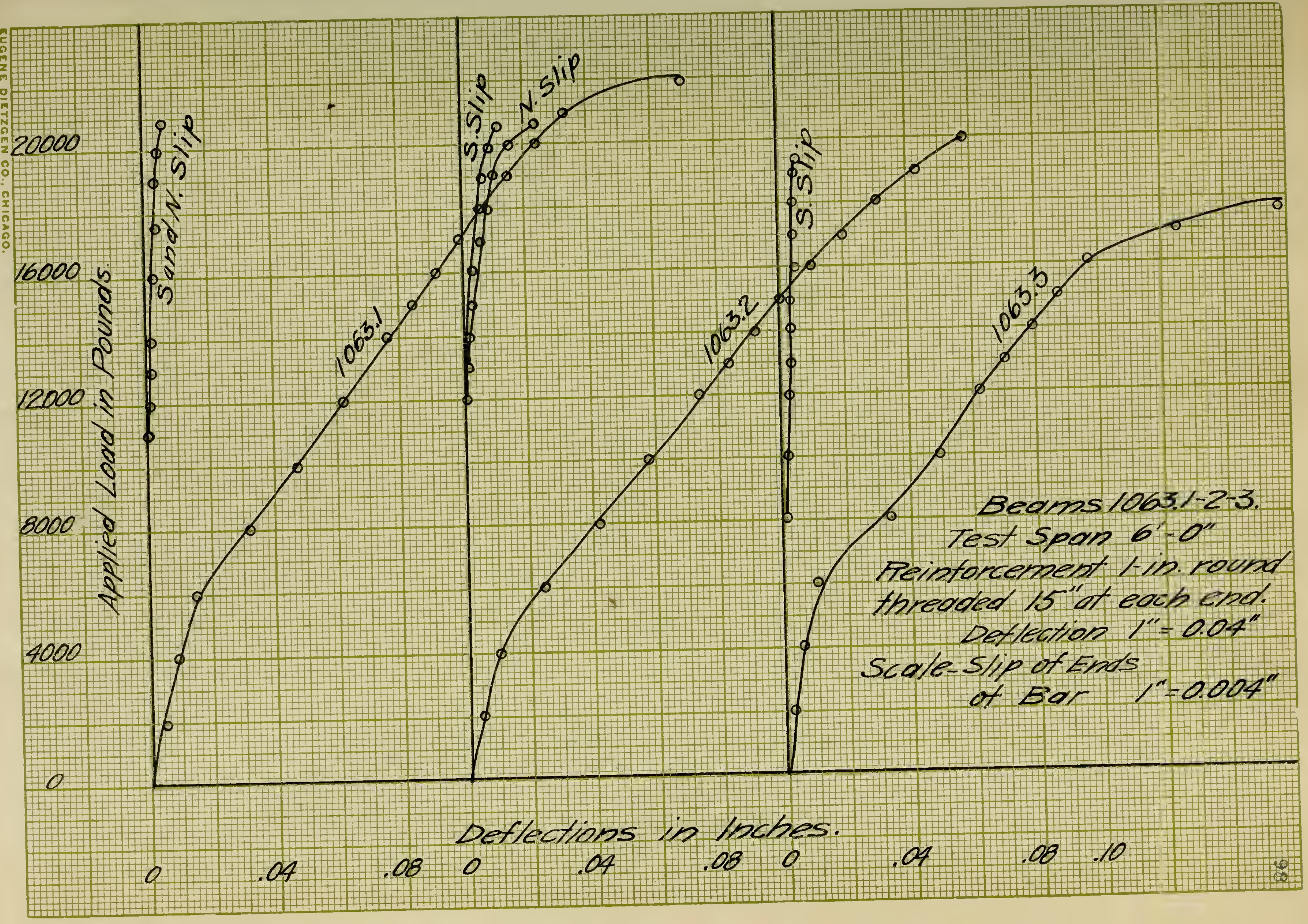

94
32000
28
24
20
16
12
8000
4000
0
Applied Load in Pounds
N. Slip
S. Slip
N. Slip
S. Slip
1048.4
N. Slip
S. Slip
1048.5
1048.6
Beams 1048.4-5-6
Test Span 6'-0"
Reinforcement
1⅛-in. cor. round.
Deflection 1"=0.04
Scale - Slip of Ends
of Bar 1"=0.004"
Deflections in Inches.
0
.02
.04
.06
0
.02
.04
.06
0
.02
.04
.06
.08


Beams 1061.1-2-3
Test Span 6'-0"
Reinforcement 1-in round
threaded 27" at each end.
Deflection 1"=0.04"
Scale Slip of Ends
of Bar 1"=0.004"
1061.3
1061.2
1061.1
N.Slip
S.Slip
N.Slip
N.Slip
S.Slip
Deflections in Inches.
.10
.08
.04
0
.08
.04
0
.08
.04
0
Applied Load in Pounds
20000
16000
12000
8000
4000
0


Beams 1061-4-5-6.
Test Span 6'-0"
Reinforcement. 1-in. round
threaded 27" at each end.
Deflection 1" = 0.04"
Scale - Slip of Ends
of Bar. 1" = 0.004"
1061.4
1061.5
1061.6
S. Slip
N. Slip
S. Slip
Applied Load in Pounds.
Deflections in Inches.
0
4000
8000
12000
16000
20000
0
.04
.08
0
.04
.08
0
.04
.08
.10



Beams 1062.1-2-3.
Test Span 6'-0"
Reinforcement 1-in round
threaded 21" at each end.
Deflection 1"=0.04"
Scale- Slip of Ends
of Bar 1"=0.004"
Applied Load in Pounds.
20000
16000
12000
8000
4000
0
Deflections in Inches.
0
.04
.08
0
.04
.08
0
.04
.08
.10
1062.1
1062.2
1062.3
S. Slip
N. Slip
S. Slip
N. Slip
N and S. Slip.



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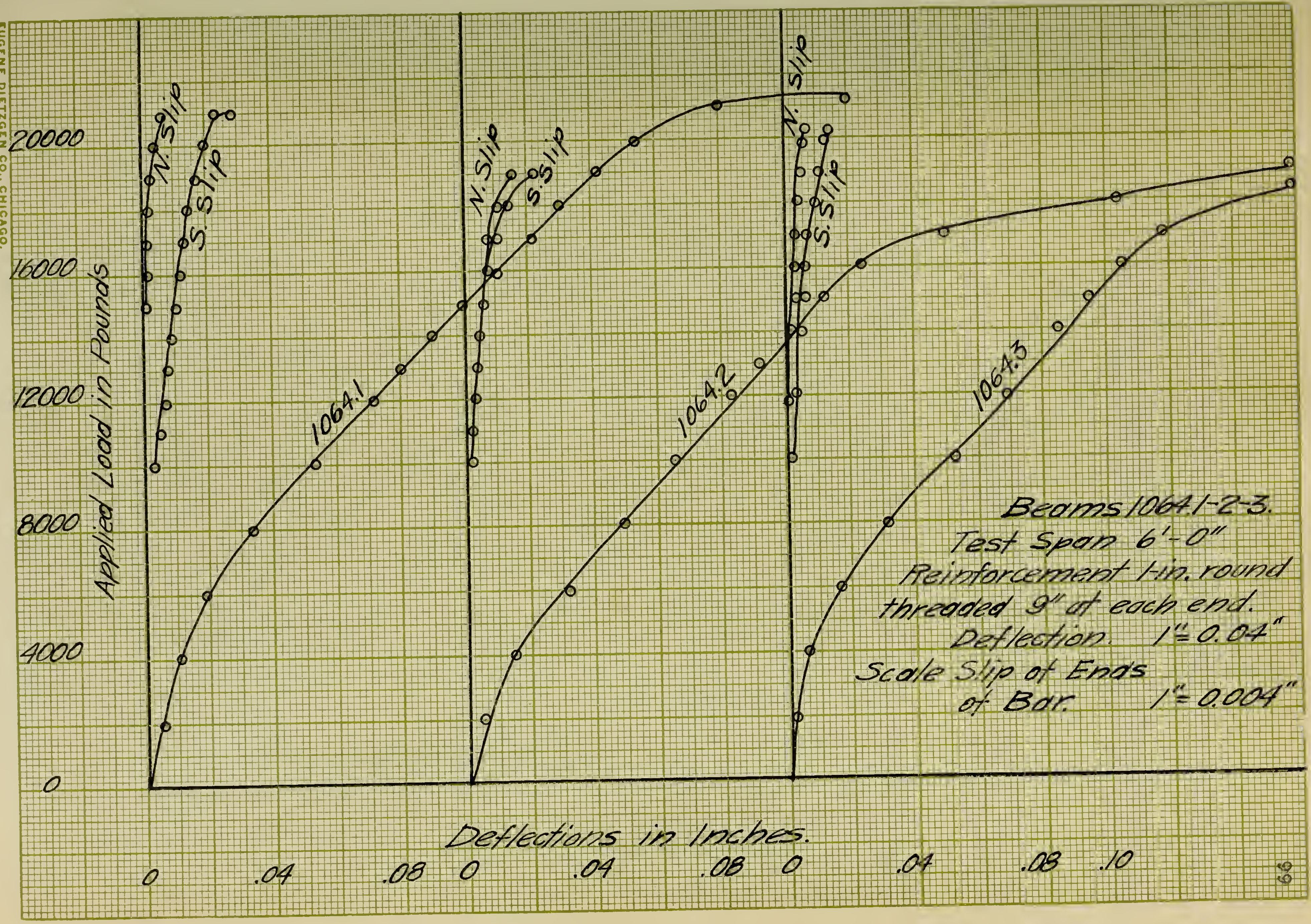
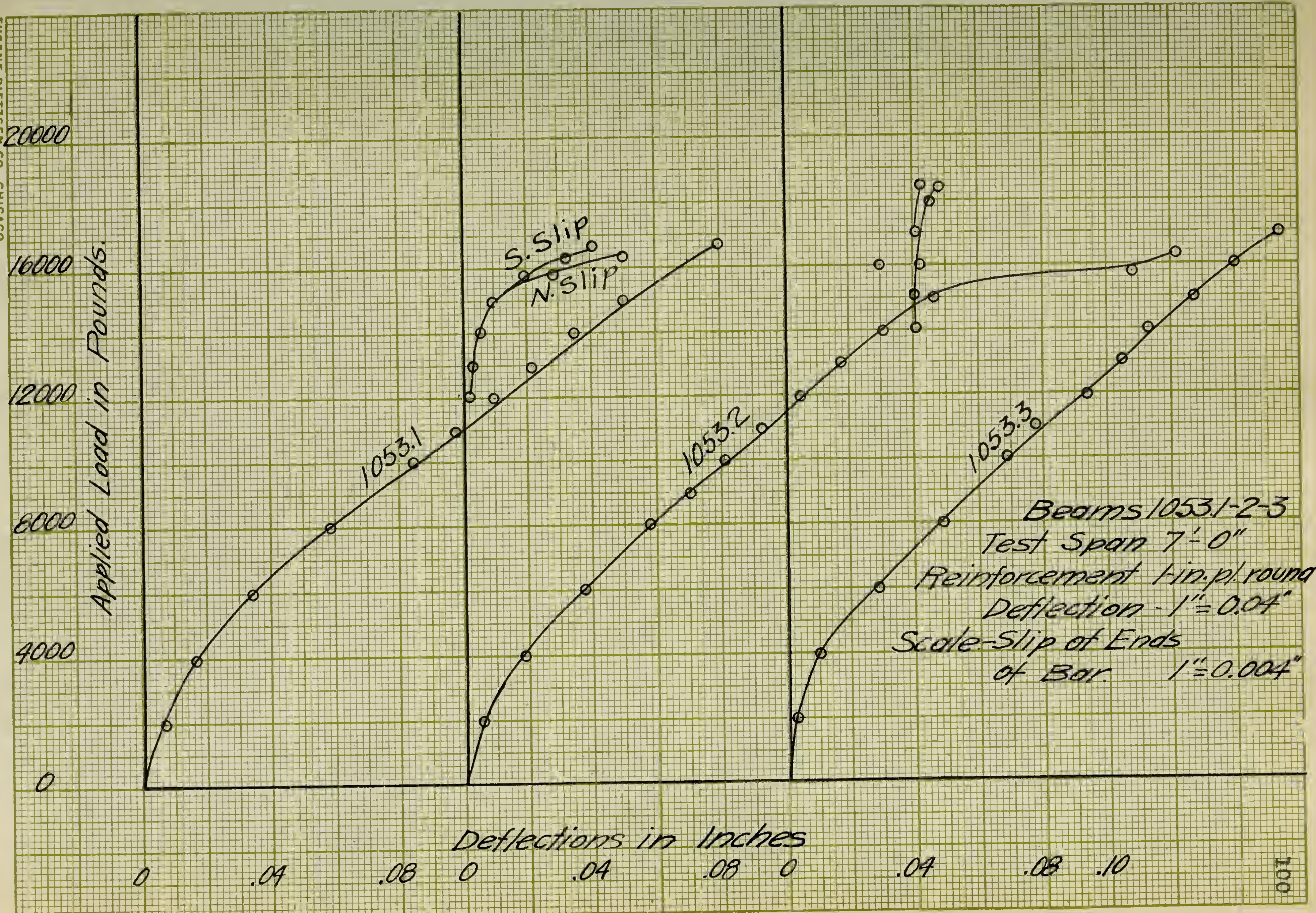
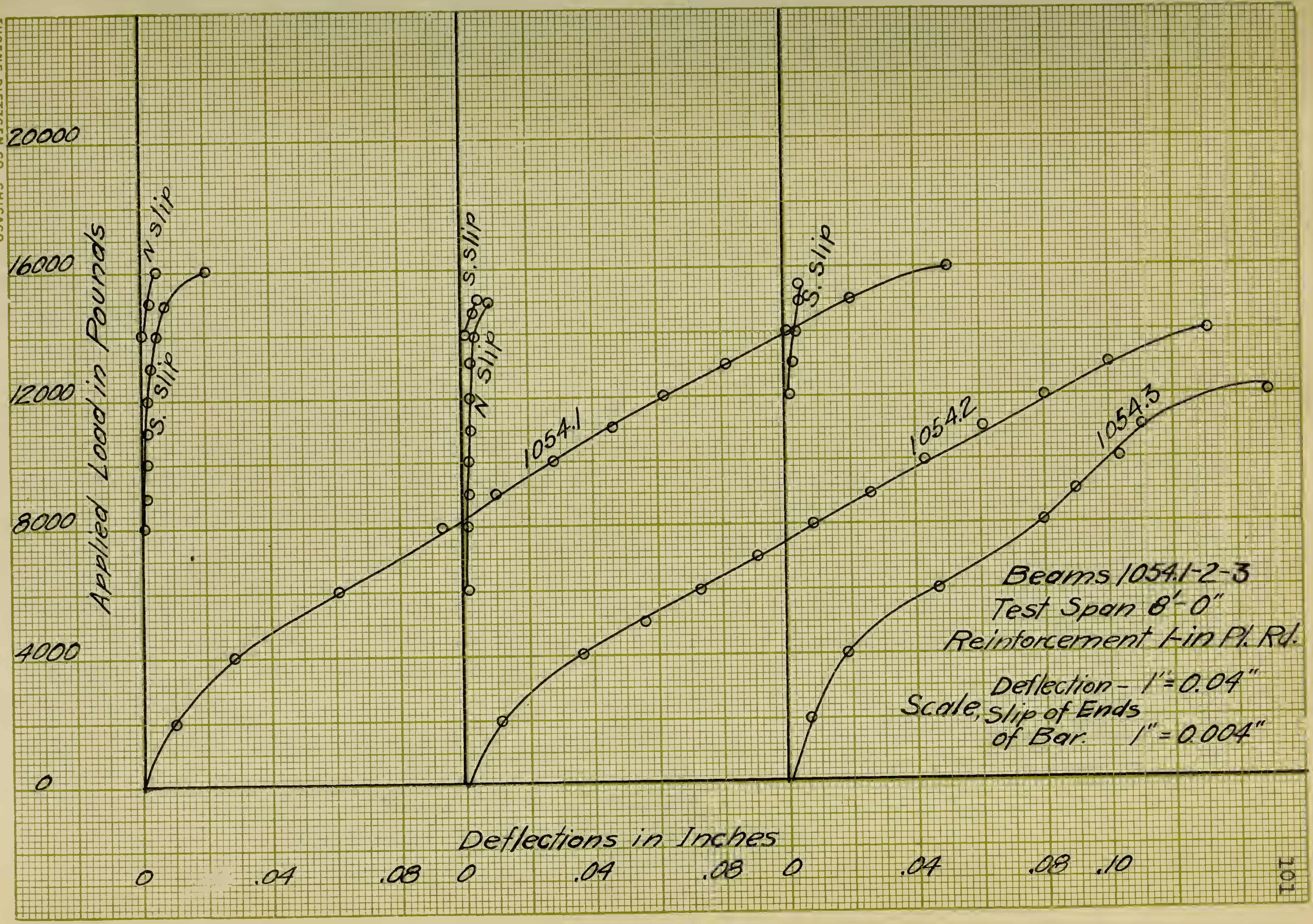
98

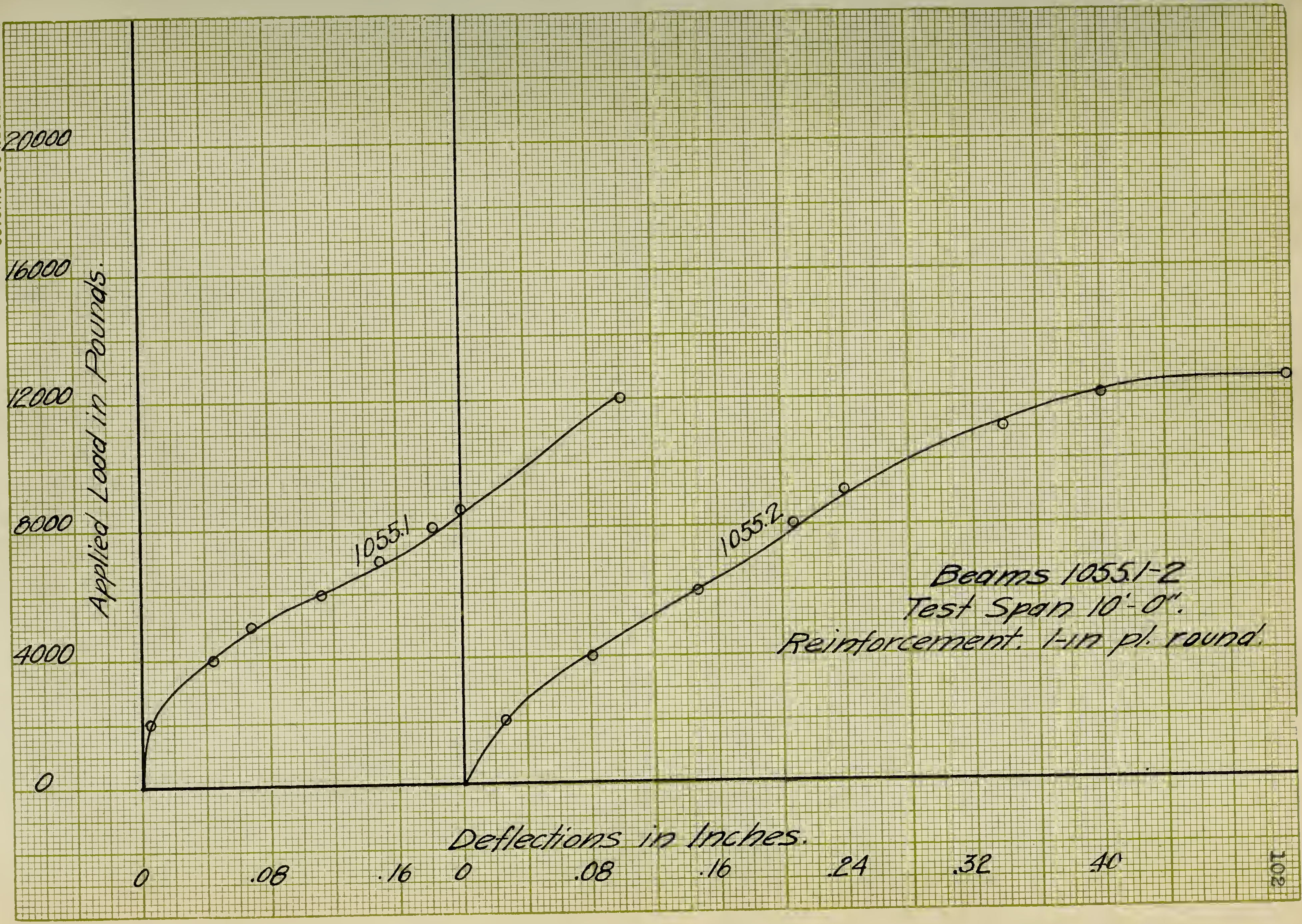

Beams 1064.1-2-3.
Test Span 6'-0"
Reinforcement 1-in. round
threaded 9" at each end.
Deflection. 1" = 0.04"
Scale Slip of Ends
of Bar. 1" = 0.004"
Applied Load in Pounds
Deflections in Inches.
1064.1
1064.2
1064.3
N. Slip
S. Slip
0
4000
8000
12000
16000
20000
.04
.08
.10
99

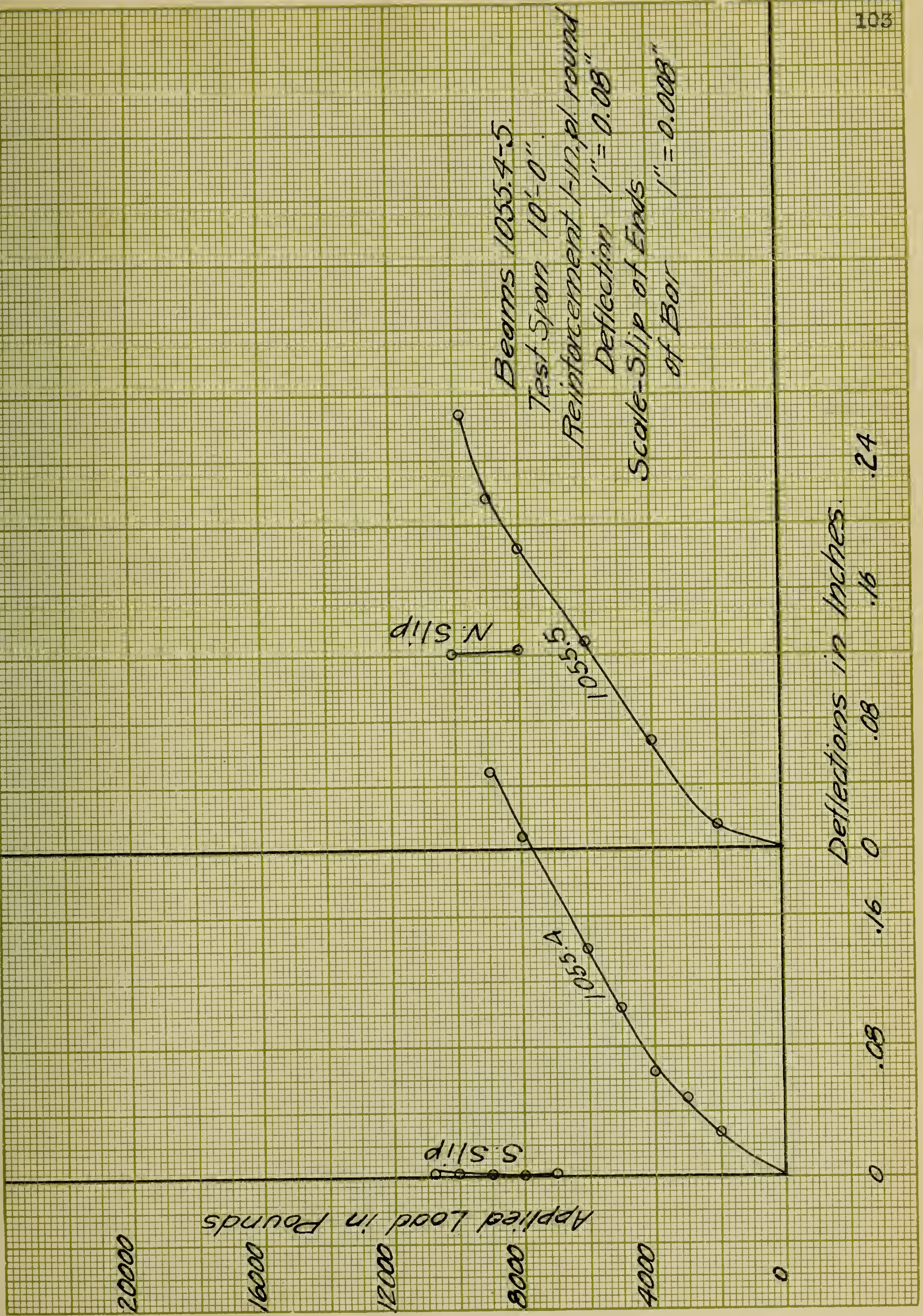


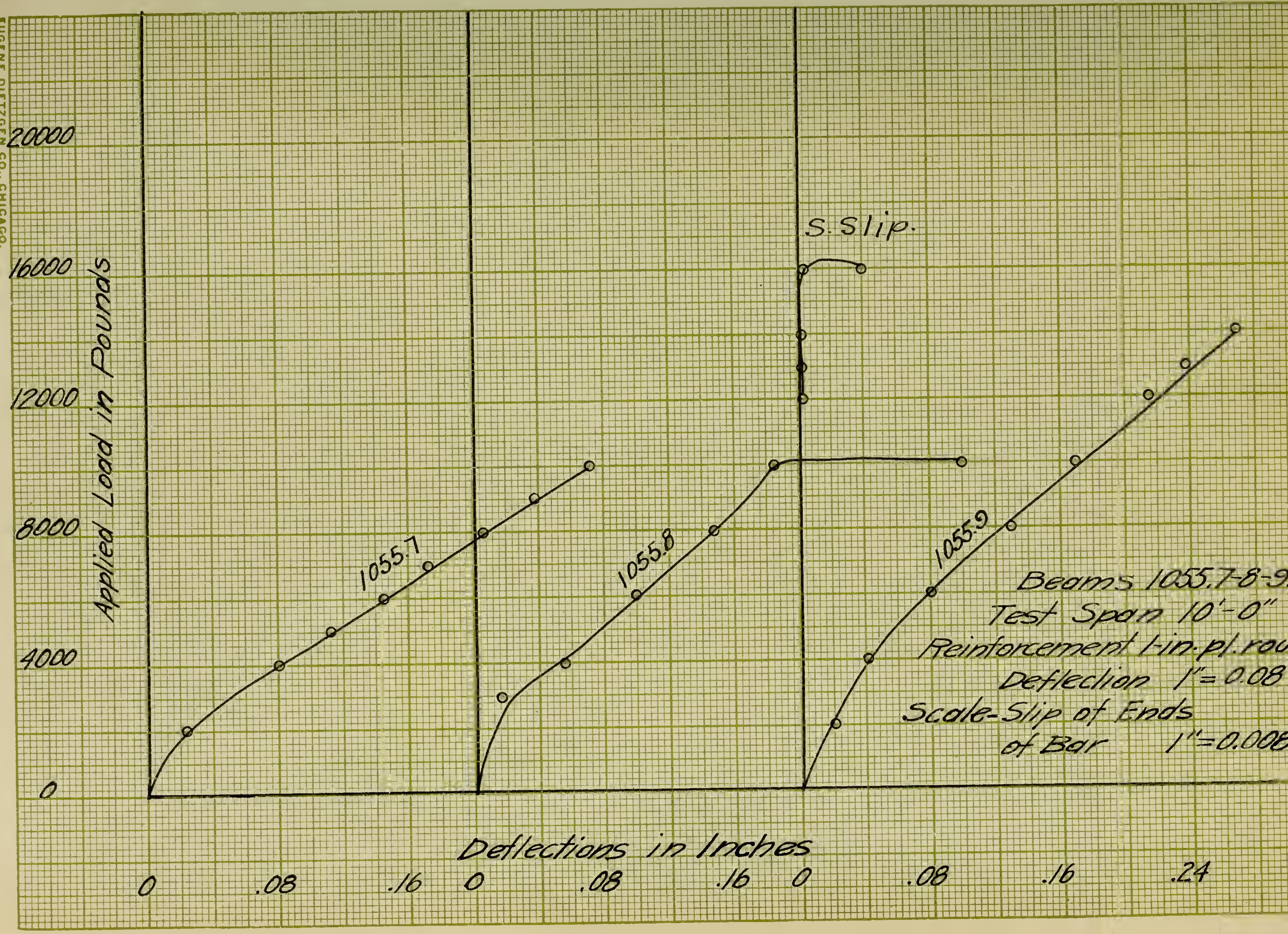
Beams 1053.1-2-3
Test Span 7'-0"
Reinforcement 1-in. pl. round
Deflection - 1" = 0.04"
Scale-Slip of Ends
of Bar. 1" = 0.004"
1053.1
1053.2
1053.3
S. Slip
N. Slip
Applied Load in Pounds.
0
4000
8000
12000
16000
20000
Deflections in Inches
0
.04
.08
.10
100

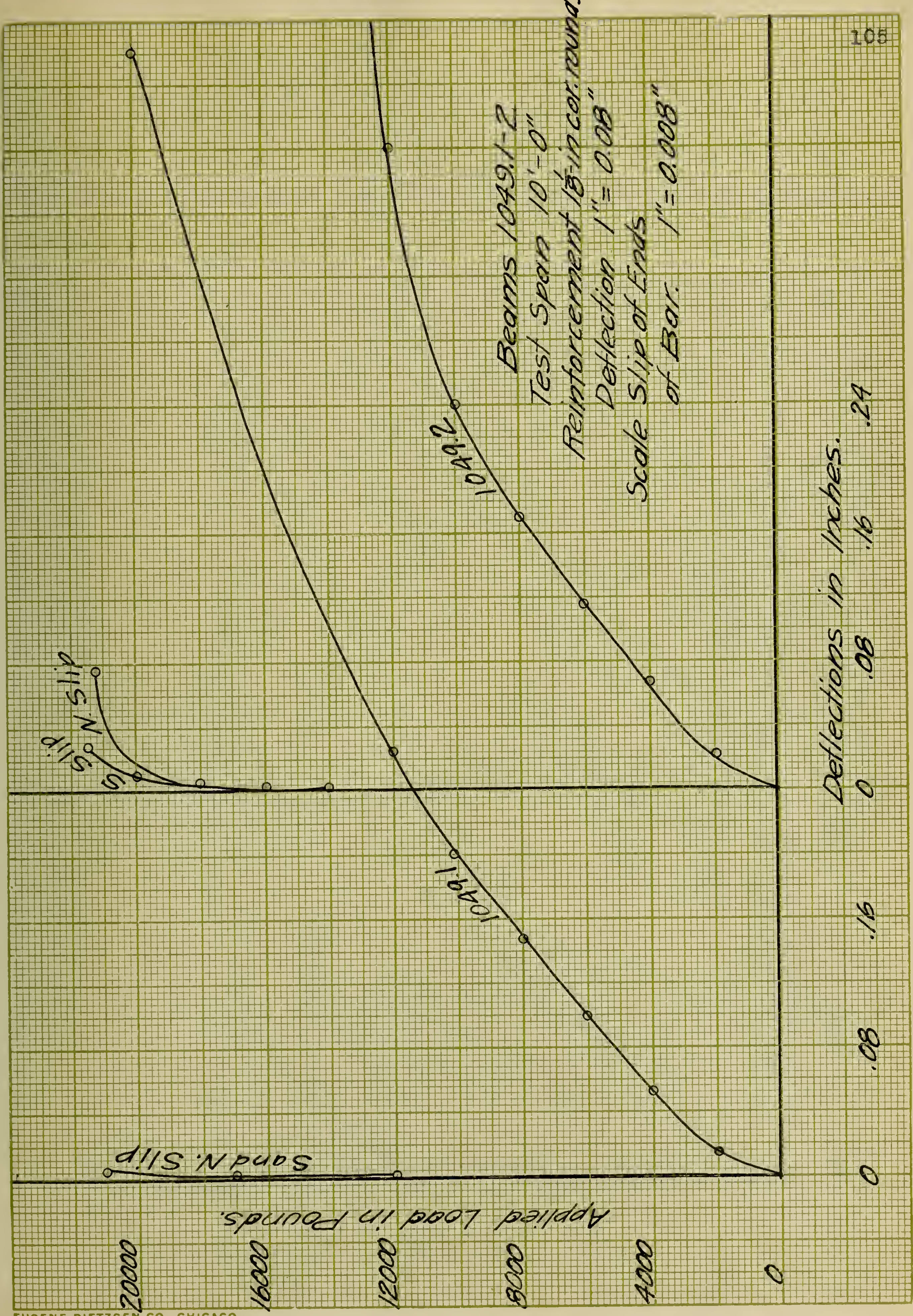


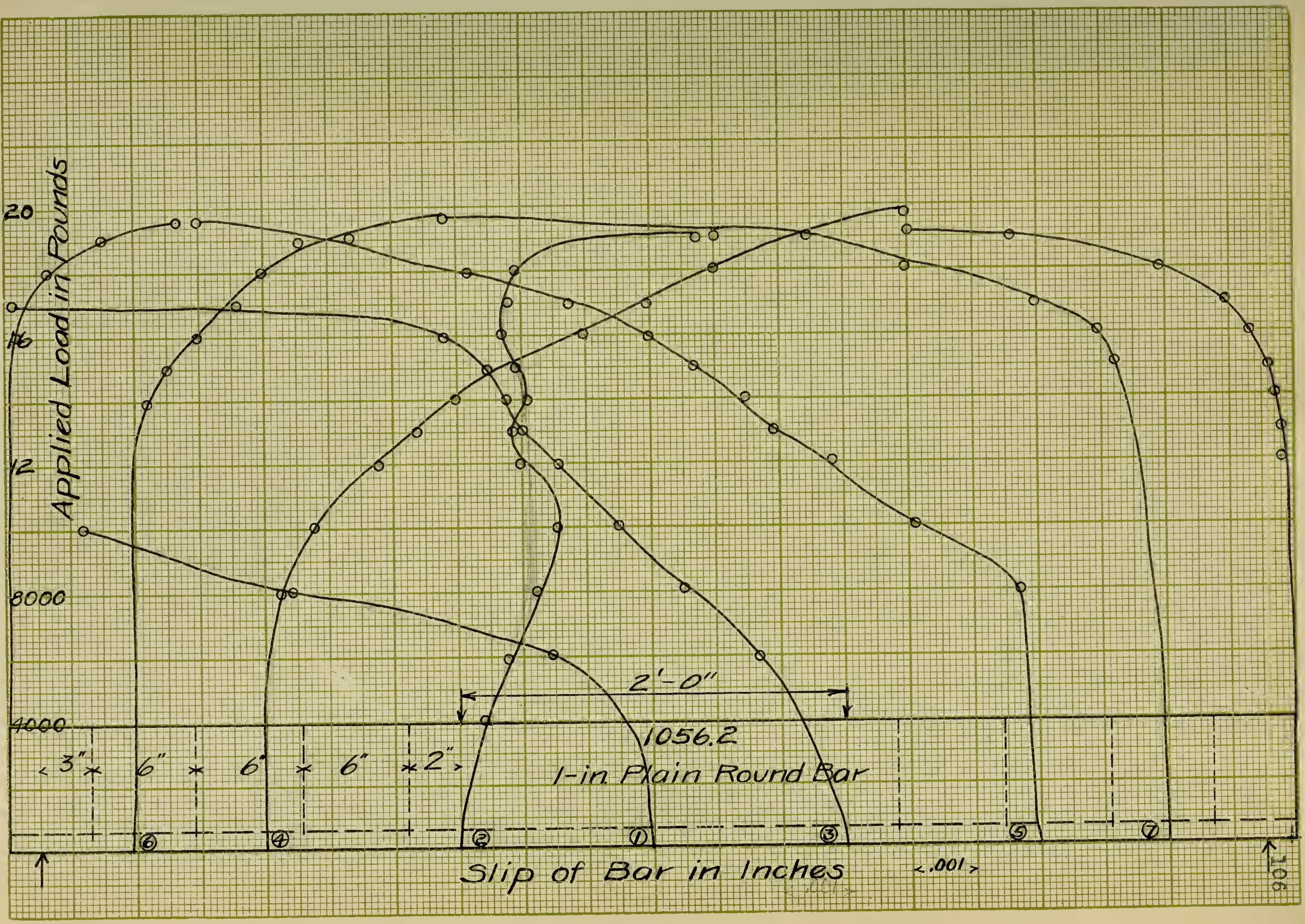
Beams 1054.1-2-3
Test Span 8'-0"
Reinforcement 1-in Pl. Rd.
Deflection - 1" = 0.04"
Scale, Slip of Ends of Bar. 1" = 0.004"
Applied Load in Pounds
20000
16000
12000
8000
4000
0
Deflections in Inches
0
.04
.08
0
.04
.08
0
.04
.08
.10
1054.1
1054.2
1054.3
N. slip
S. slip
S. slip
N. slip
S. slip

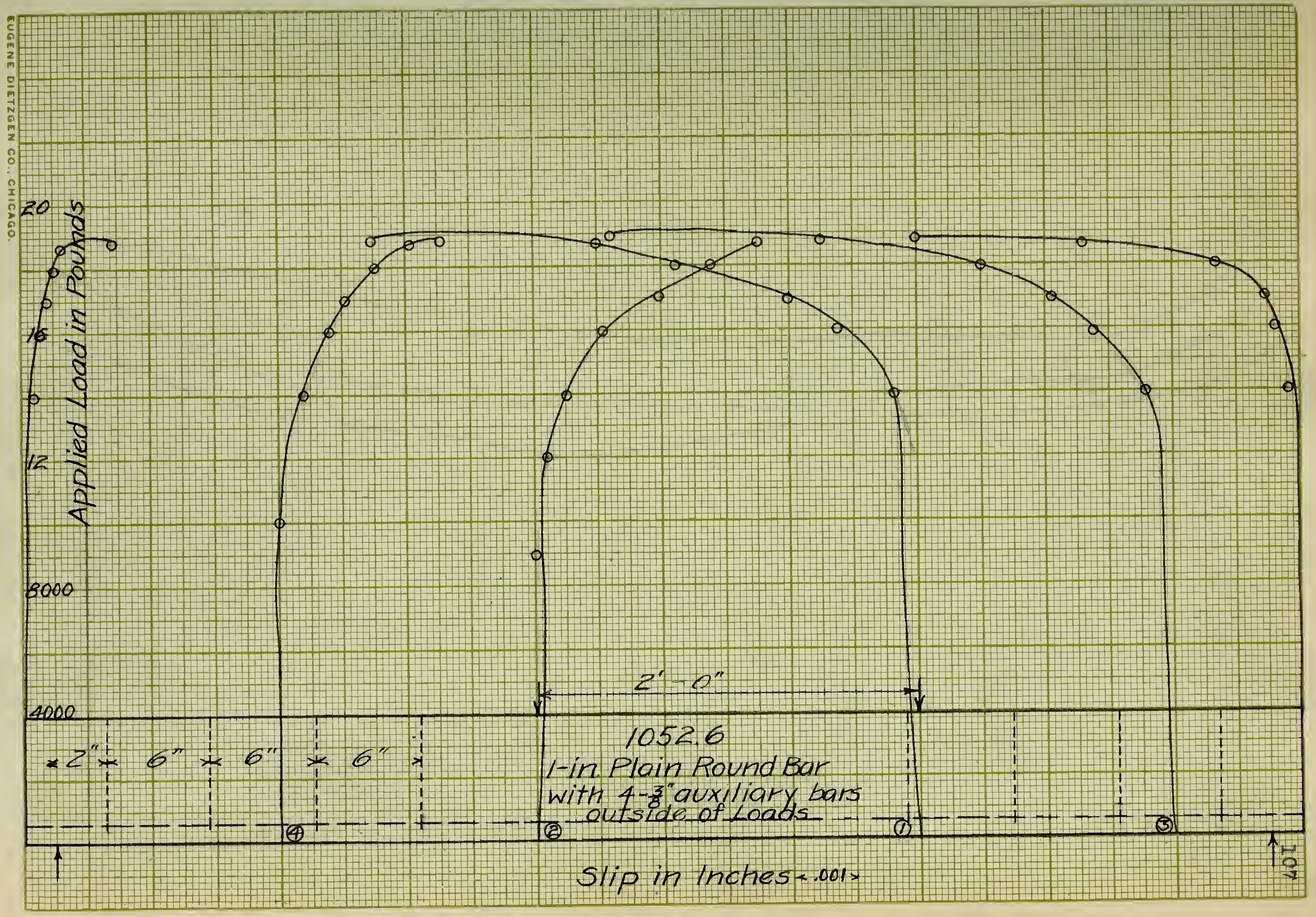

Beams 1055.1-2
Test Span 10'-0".
Reinforcement. 1-in pl. round.
1055.1
1055.2
Applied Load in Pounds.
20000
16000
12000
8000
4000
0
Deflections in Inches.
0
.08
.16
0
.08
.16
.24
.32
.40

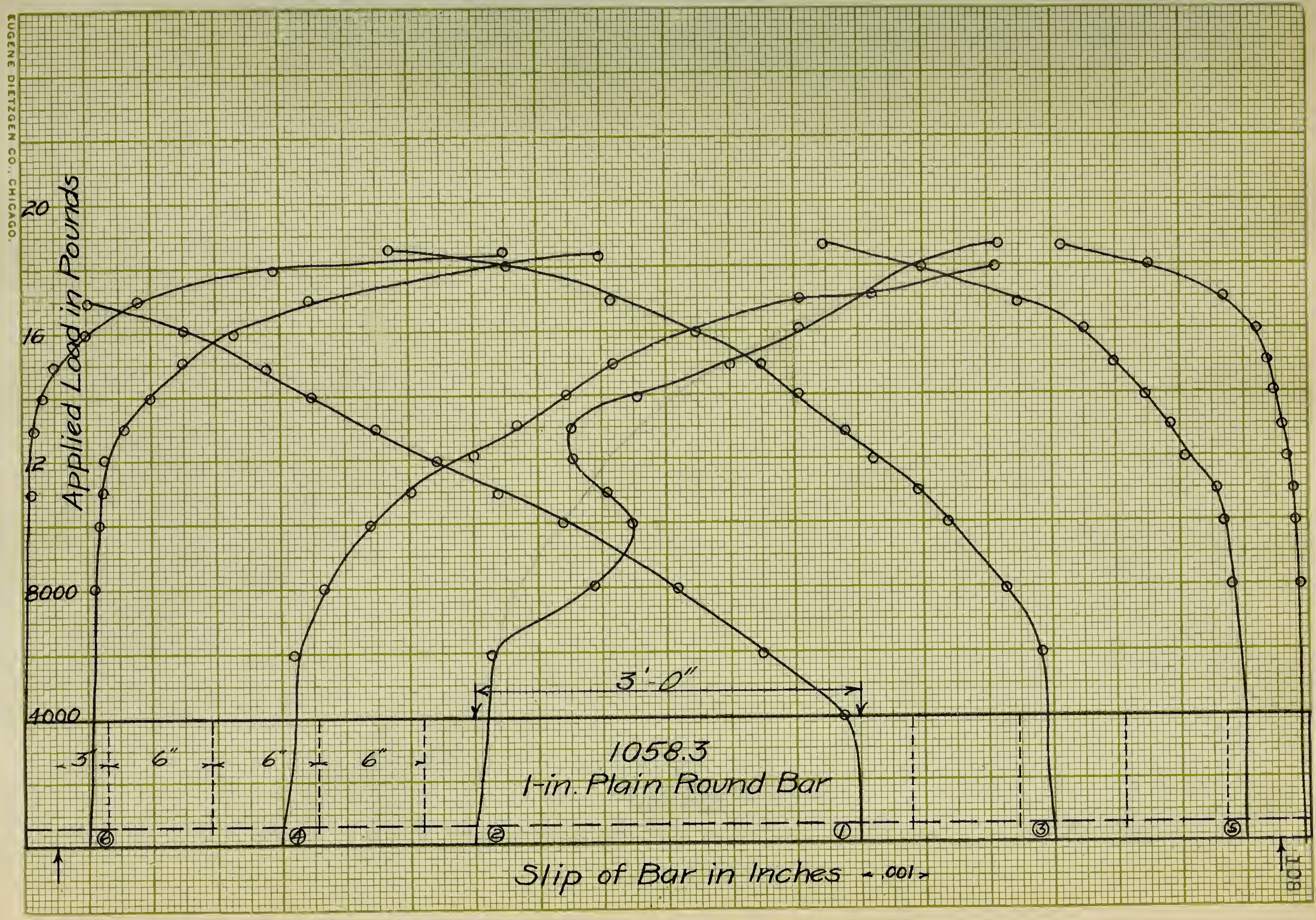

Beams 1055:4-5.
Test Span 10'-0"
Reinforcement 1-in. pl. round
Deflection 1" = 0.08"
Scale-Slip of Ends
of Bar 1" = 0.008"
N. Slip
S. Slip
1055:5
1055:4
Deflections in Inches
.24
.16
.08
0
.16
.08
0
Applied Load in Pounds
20000
16000
12000
8000
4000
0


S. Slip.
1055.7
1055.8
1055.9
Beams 1055.7-8-9.
Test Span 10'-0"
Reinforcement 1-in. pl. round
Deflection 1" = 0.08"
Scale-Slip of Ends
of Bar 1" = 0.008"
Applied Load in Pounds
0
4000
8000
12000
16000
20000
Deflections in Inches
0
.08
.16
0
.08
.16
0
.08
.16
.24

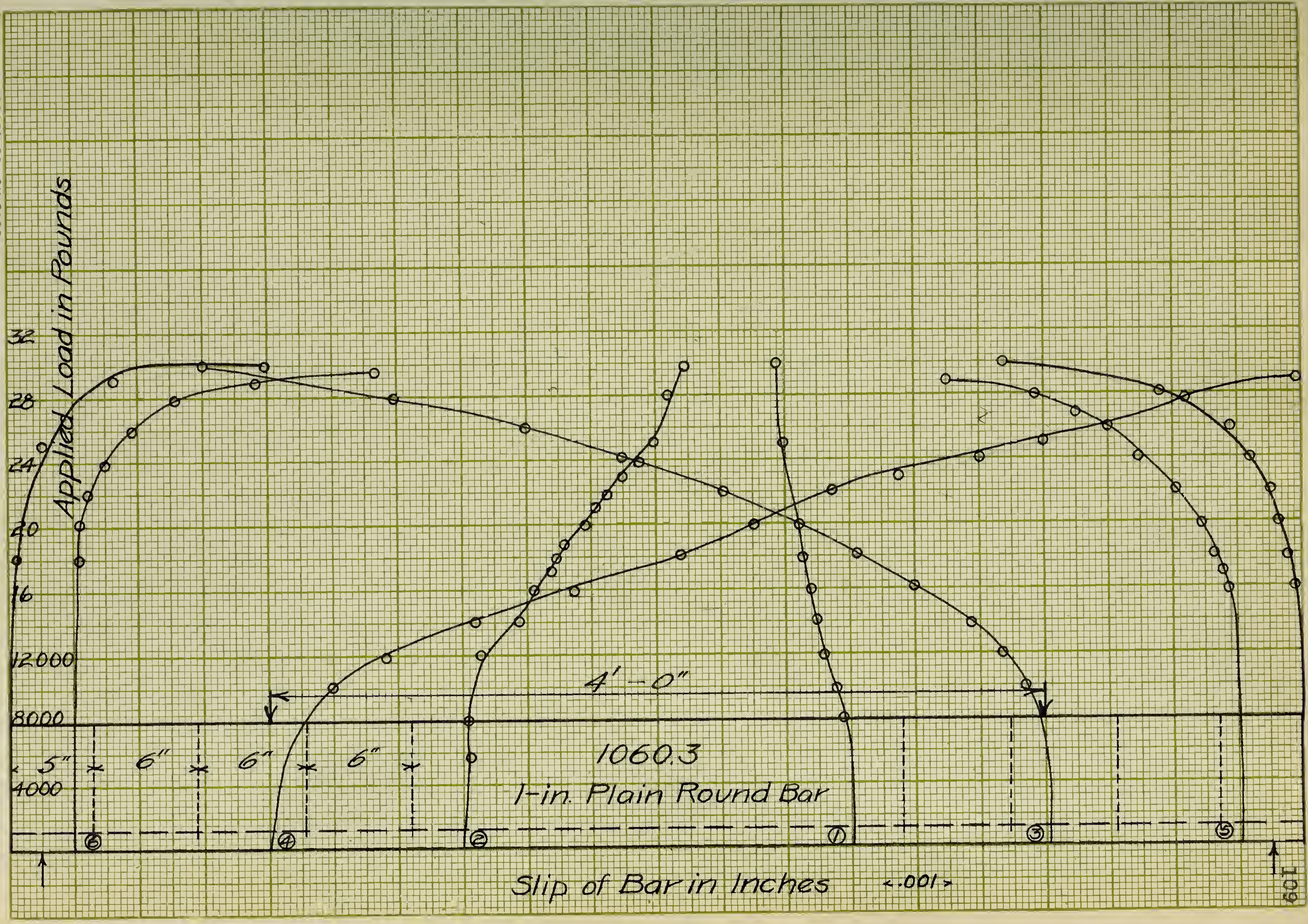

Beams 1049.1-2
Test Span 10'-0"
Reinforcement 1/8-in cor. rounds
Deflection 1" = 0.08"
Scale Slip of Ends
of Bar. 1" = 0.008"
1049.2
1049.1
S. Slip
N. Slip
S and N. Slip
Deflections in Inches.
0
.08
.16
.24
Applied Load in Pounds.
20000
16000
12000
8000
4000
0

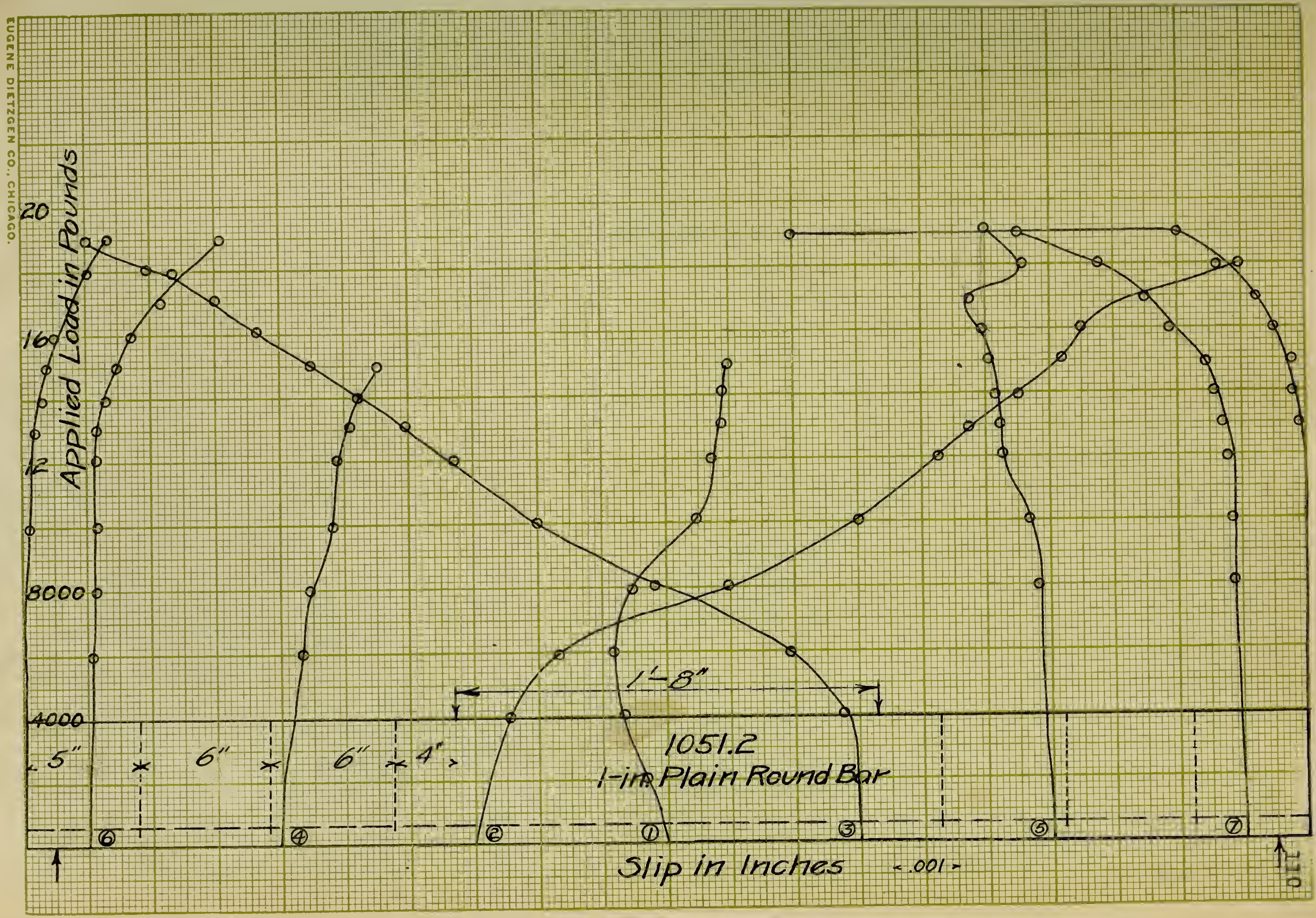

Applied Load in Pounds
20
16
12
8000
4000
2'-0"
1056.2
3"
6"
6"
6"
2"
1-in. Plain Round Bar
6
4
2
1
3
5
7
Slip of Bar in Inches
.001
106

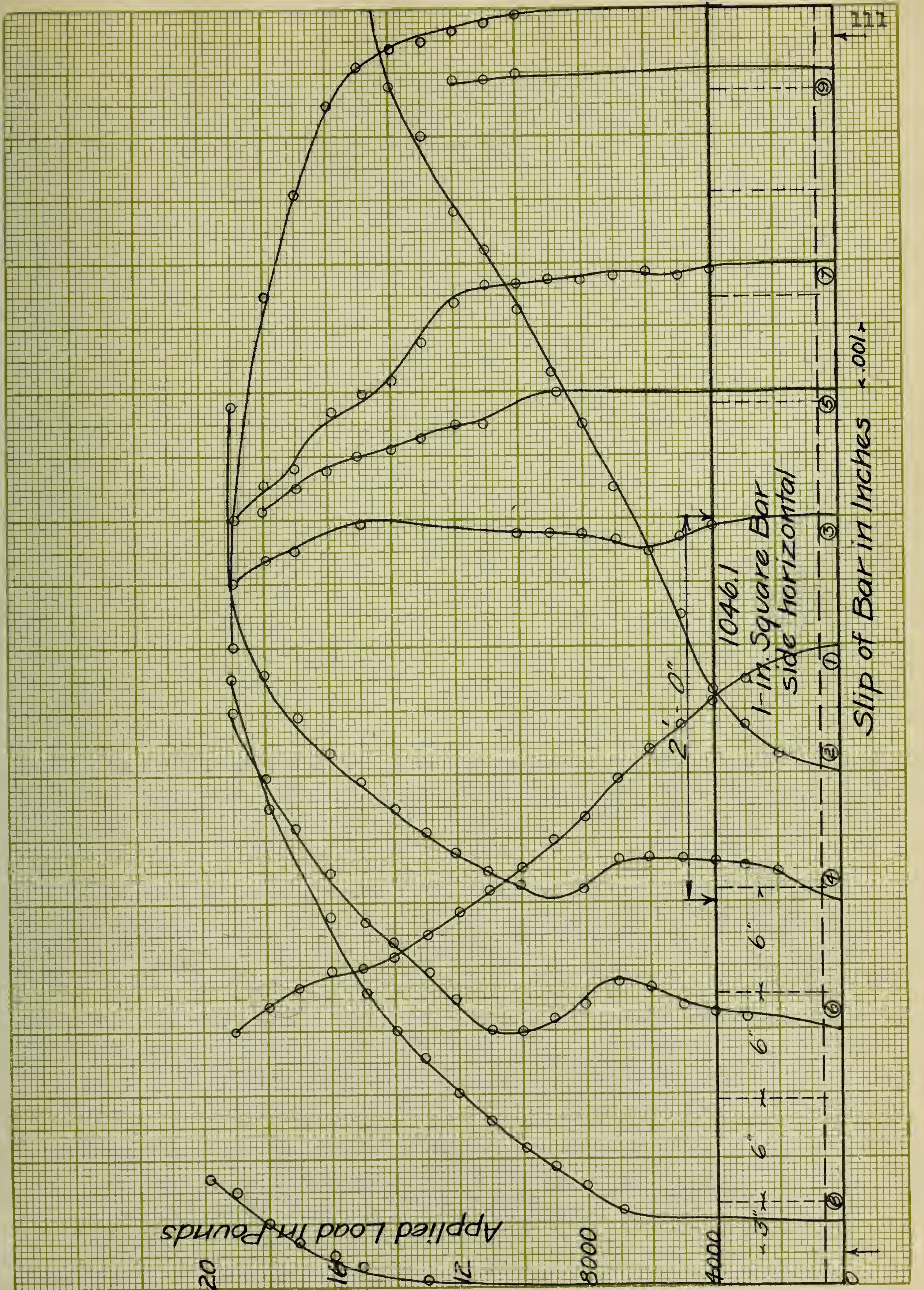

20
16
12
8000
4000
Applied Load in Pounds
2'-0"
1052.6
1-in. Plain Round Bar
with 4-$\frac{3}{8}$" auxiliary bars
outside of Loads
2"
6"
6"
6"
Slip in Inches ←.001→
107
EUGENE DIETZGEN CO., CHICAGO.

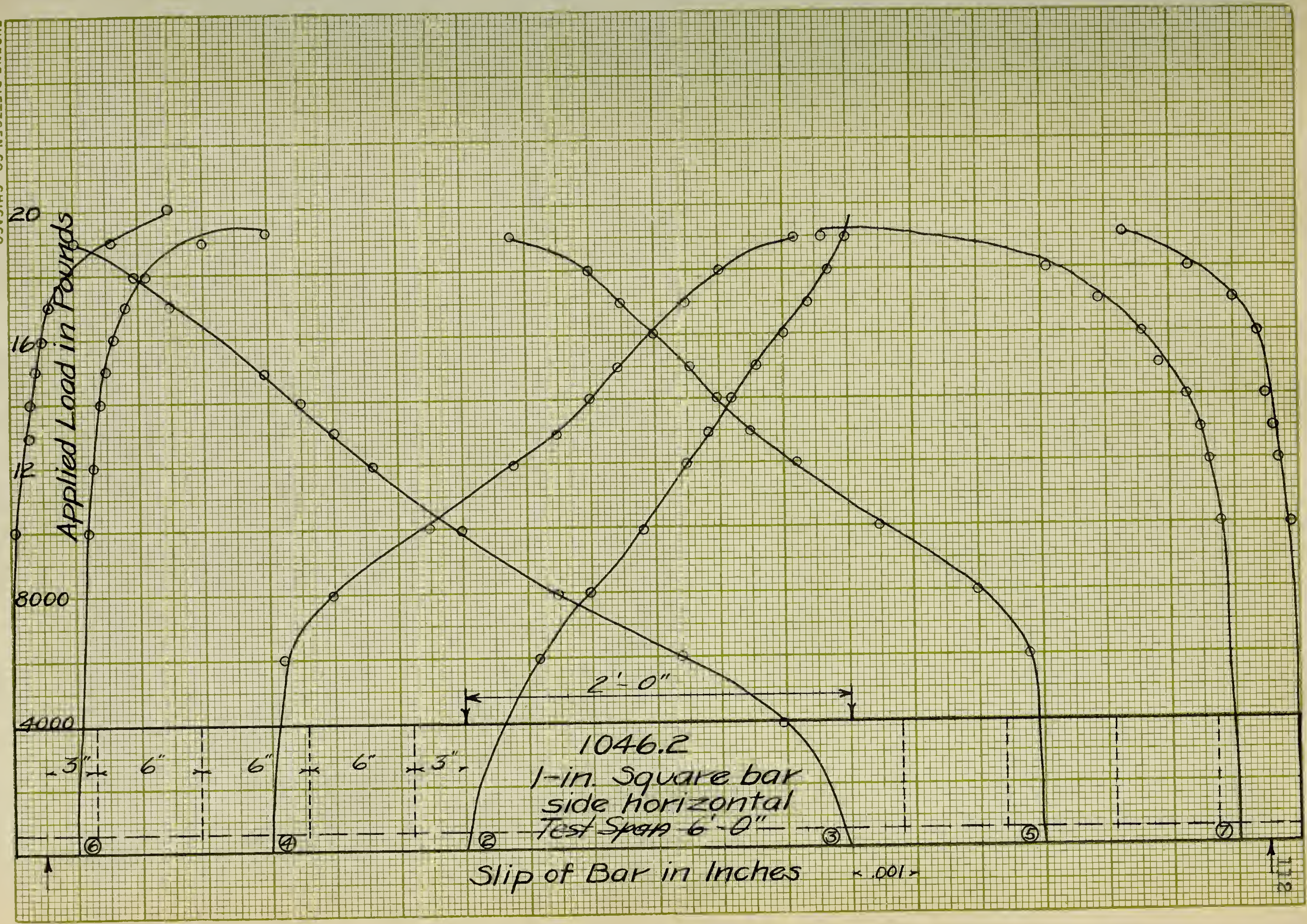


Applied Load in Pounds
20
16
12
8000
4000
3'-0"
3"
6"
6"
6"
1058.3
1-in. Plain Round Bar
Slip of Bar in Inches .001
108
EUGENE DIETZGEN CO., CHICAGO.

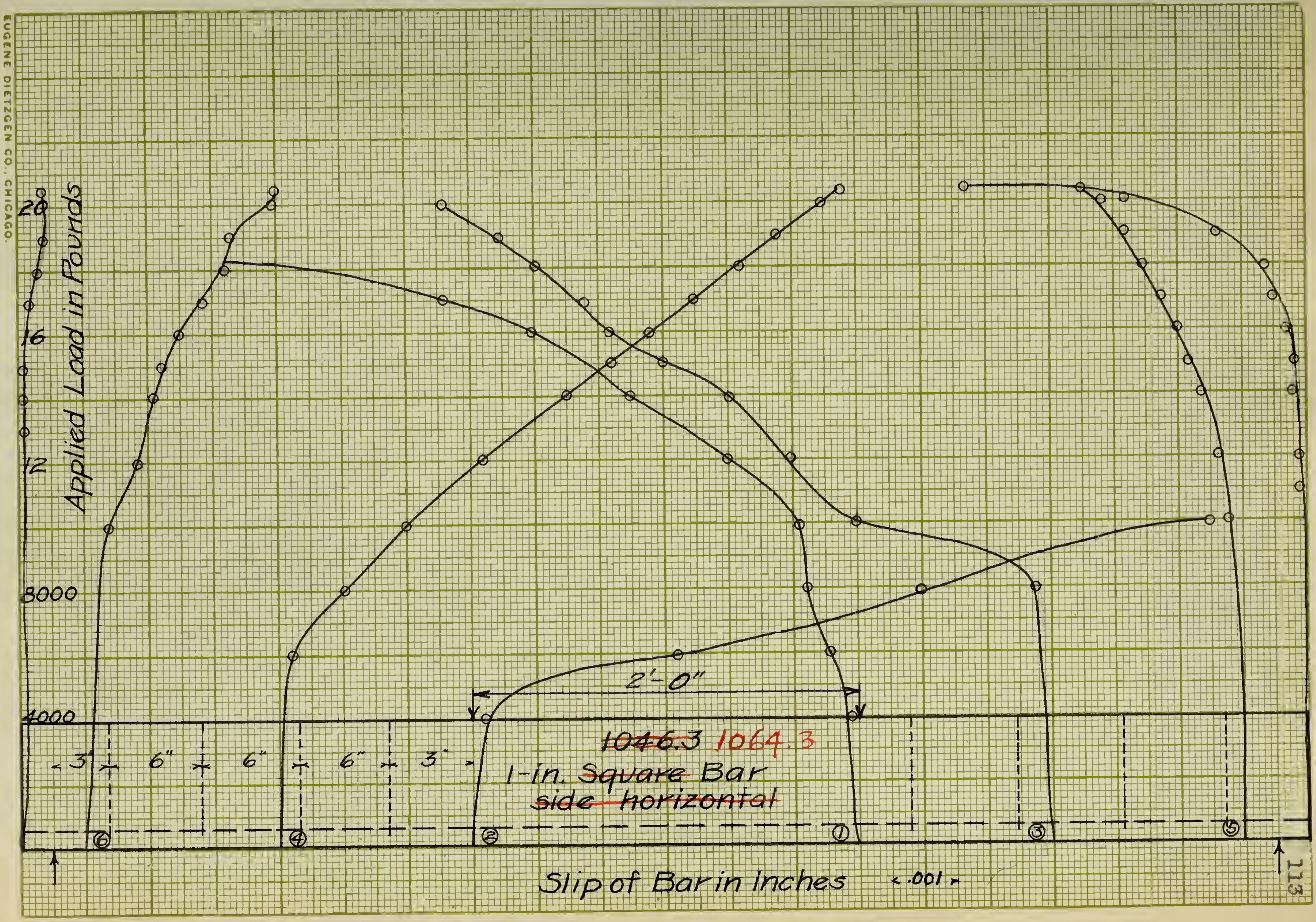

1060.3
1-in. Plain Round Bar
Applied Load in Pounds
Slip of Bar in Inches
<.001>
4'-0"
5"
6"
6"
6"
32
28
24
20
16
12000
8000
4000
1
2
3
4
5
6

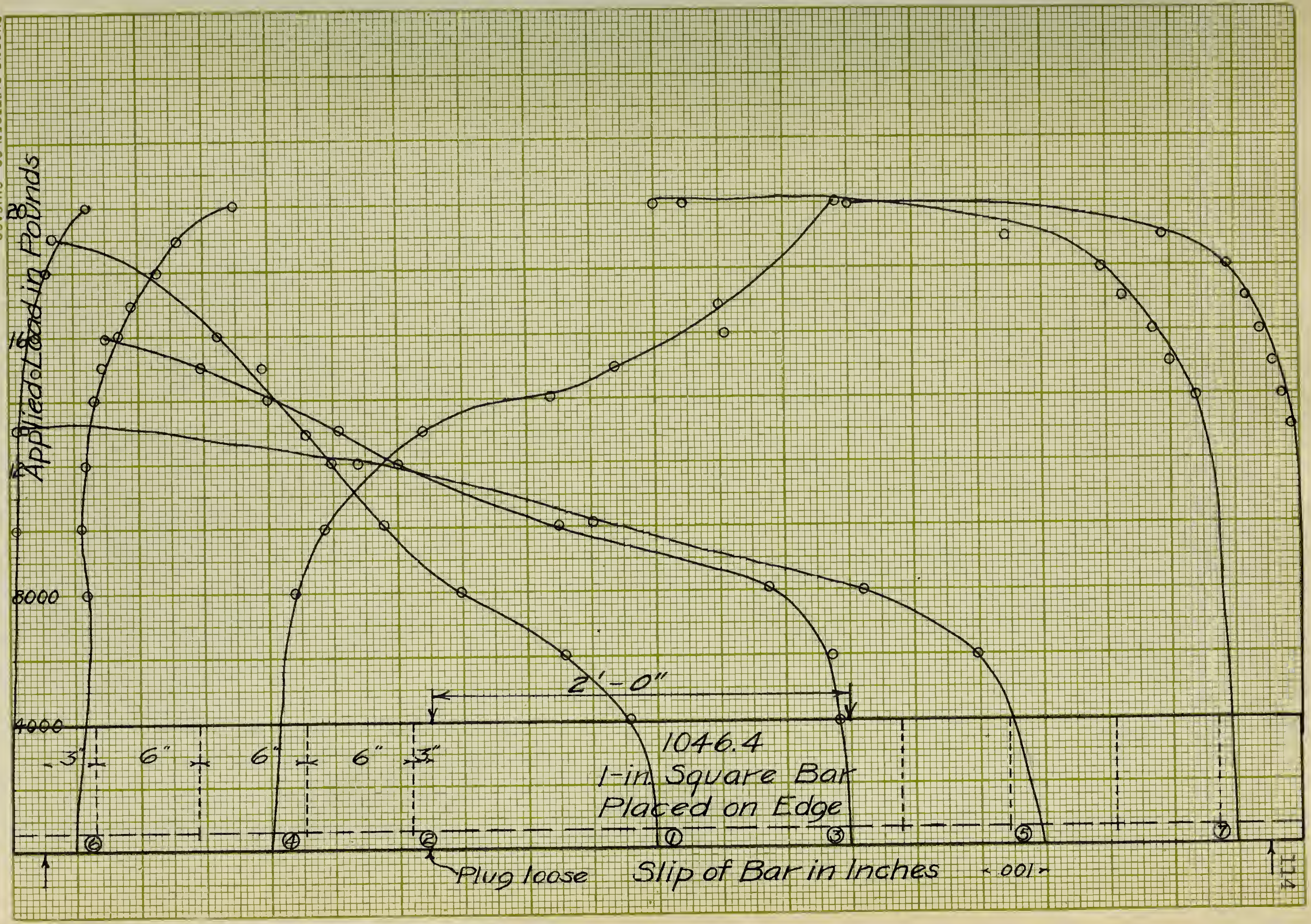

Applied Load in Pounds
20
16
12
8000
4000
5"
6"
6"
4"
1'-8"
1051.2
1-in. Plain Round Bar
Slip in Inches
.001
1
2
3
4
5
6
7
110
EUGENE DIETZGEN CO., CHICAGO.

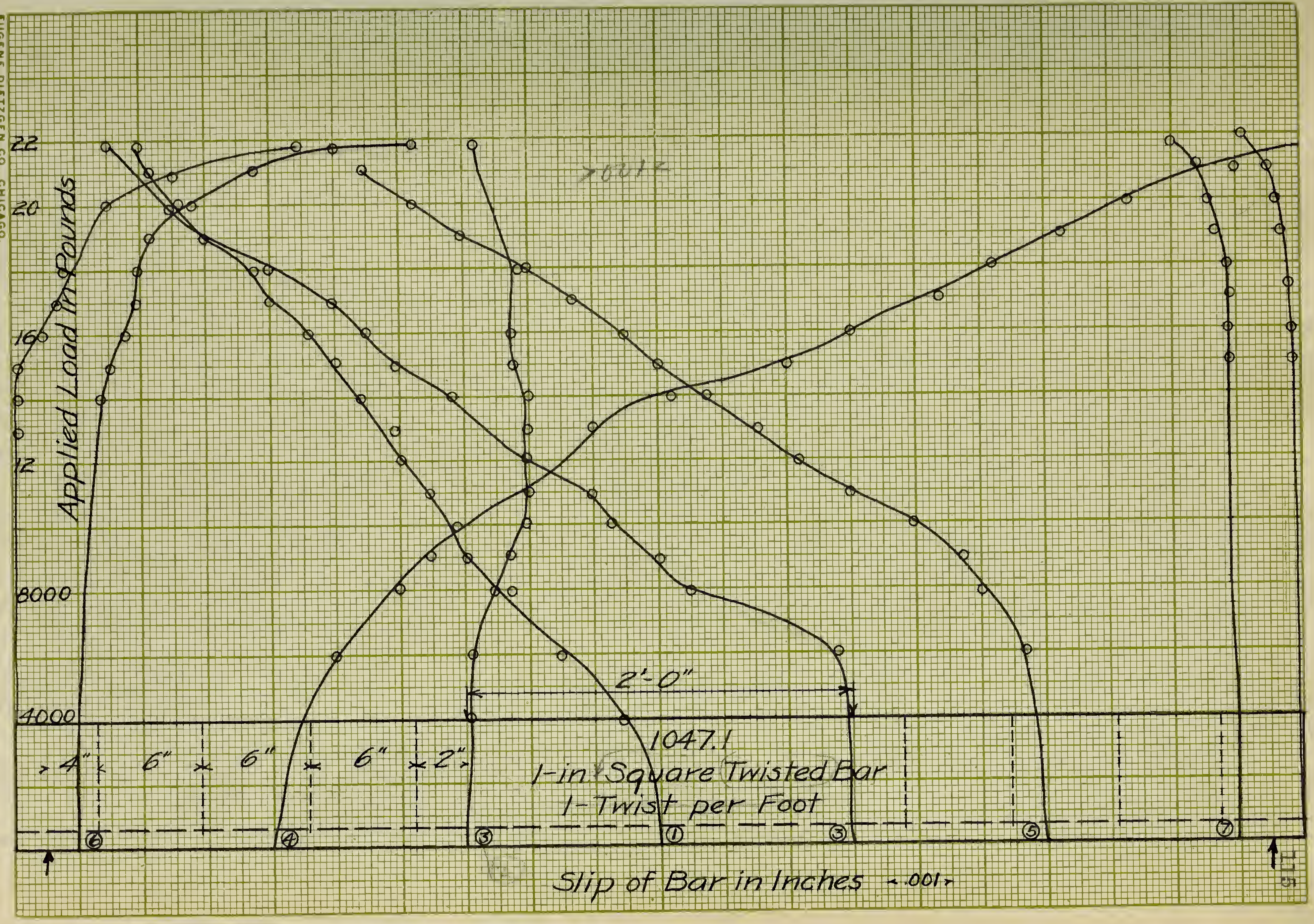

Applied Load in Pounds
Slip of Bar in Inches
<.001>
1046.1
1-in. Square Bar
side horizontal
2'-0"
6"
6"
6"
3"
20
16
12
8000
4000
0
1
2
3
4
5
6
7
8
9



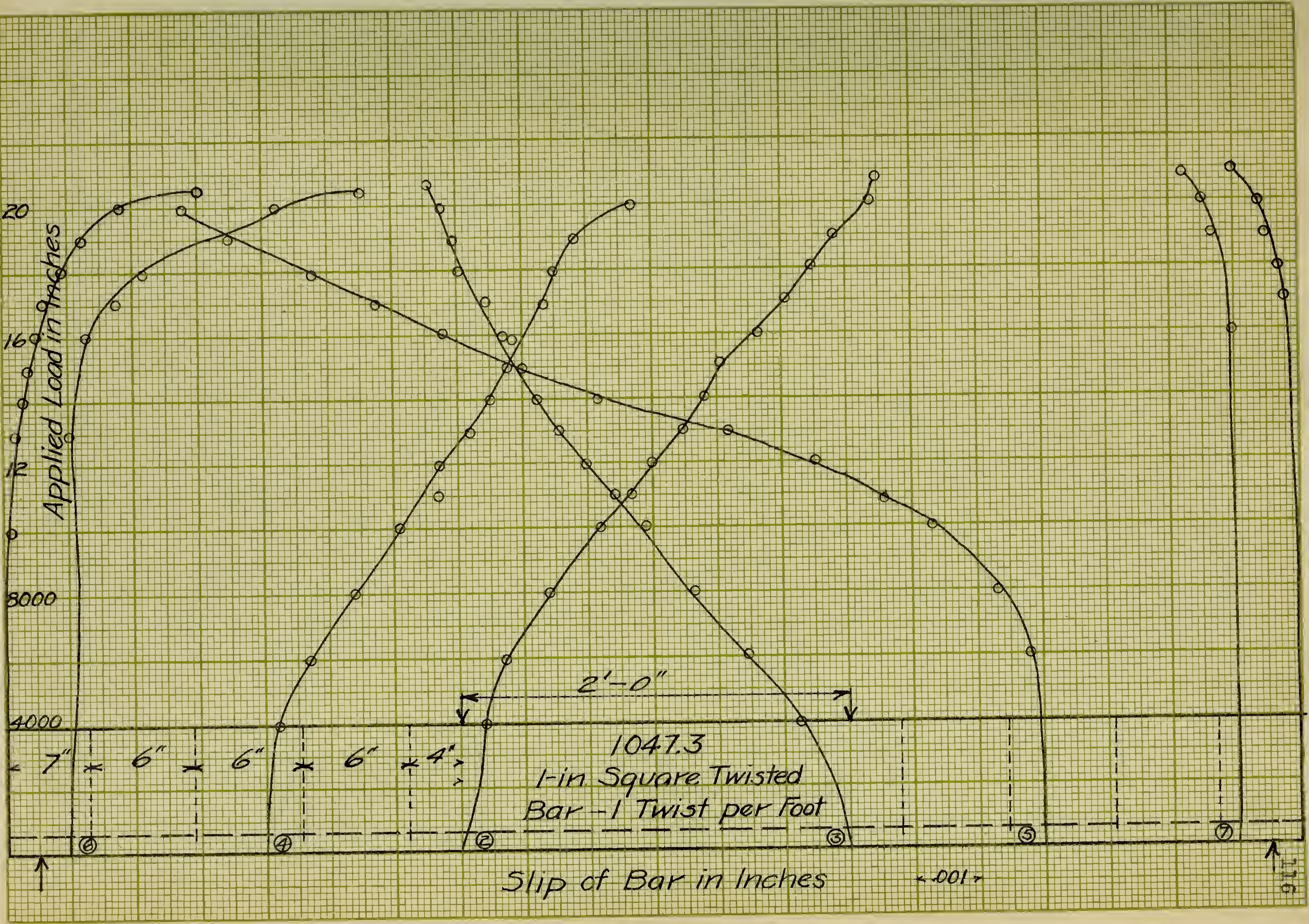
EUGENE DIETZGEN CO., CHICAGO.


Applied Load in Pounds
20
16
12
8000
4000
2'-0"
~~1046.3~~ 1064.3
1-in. ~~Square~~ Bar
~~side horizontal~~
3"
6"
6"
6"
3"
Slip of Bar in Inches
.001
EUGENE DIETZGEN CO., CHICAGO.

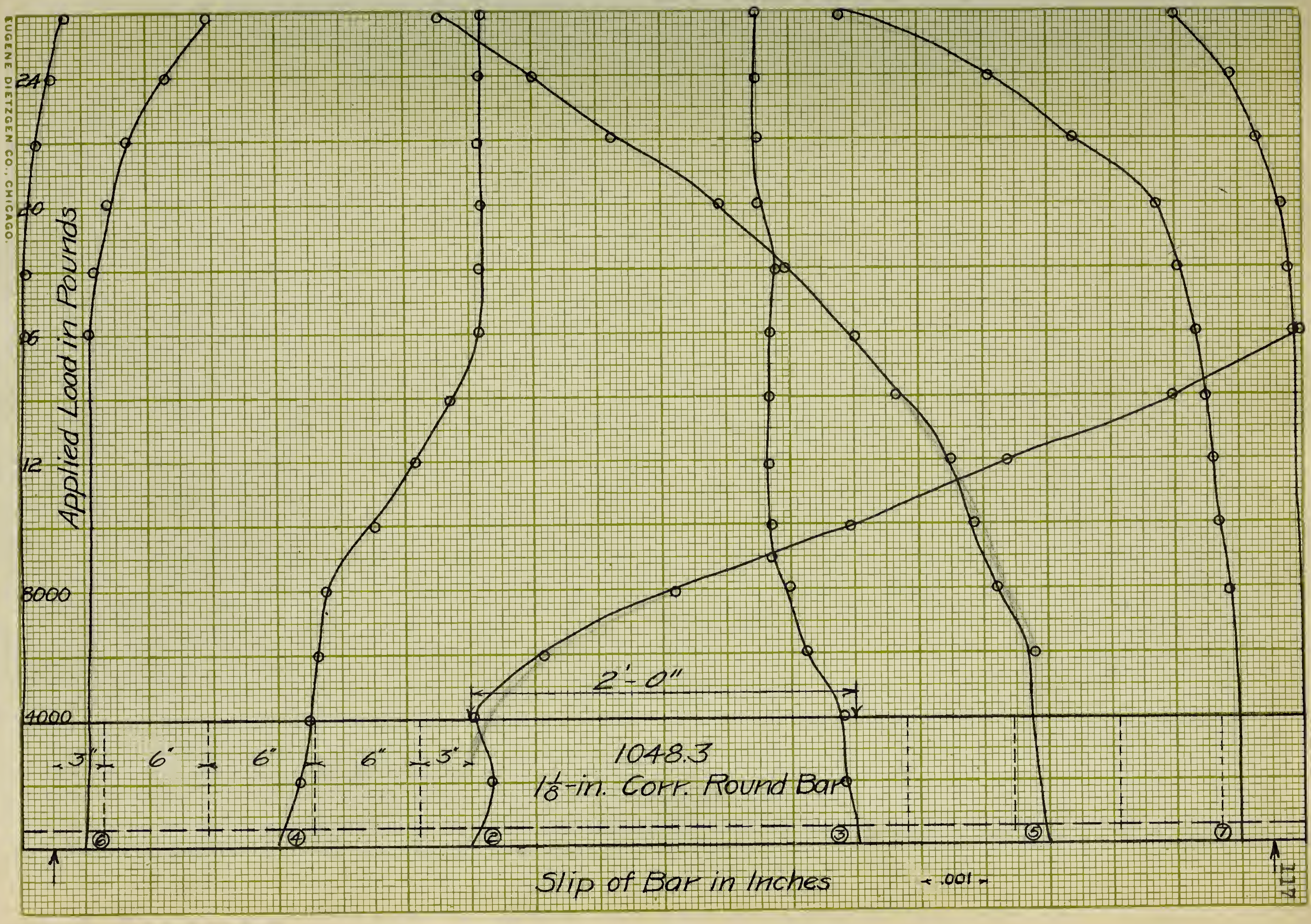

Applied Load in Pounds
20
16
12
8000
4000
3"
6"
6"
6"
3"
2'-0"
1046.4
1-in. Square Bar
Placed on Edge
Plug loose
Slip of Bar in Inches
.001
1
2
3
4
5
6
7



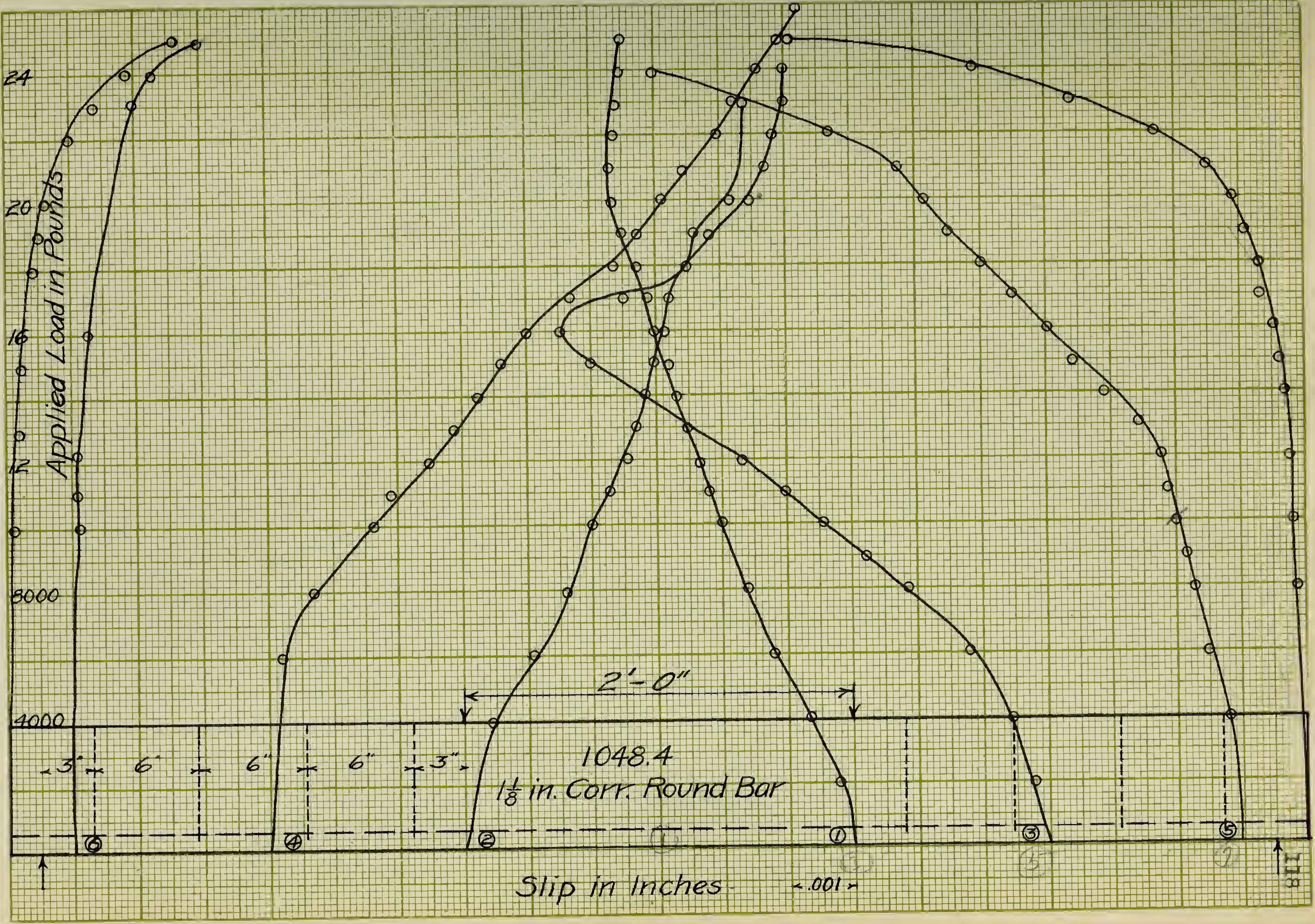
EUGENE DIETZGEN CO., CHICAGO.

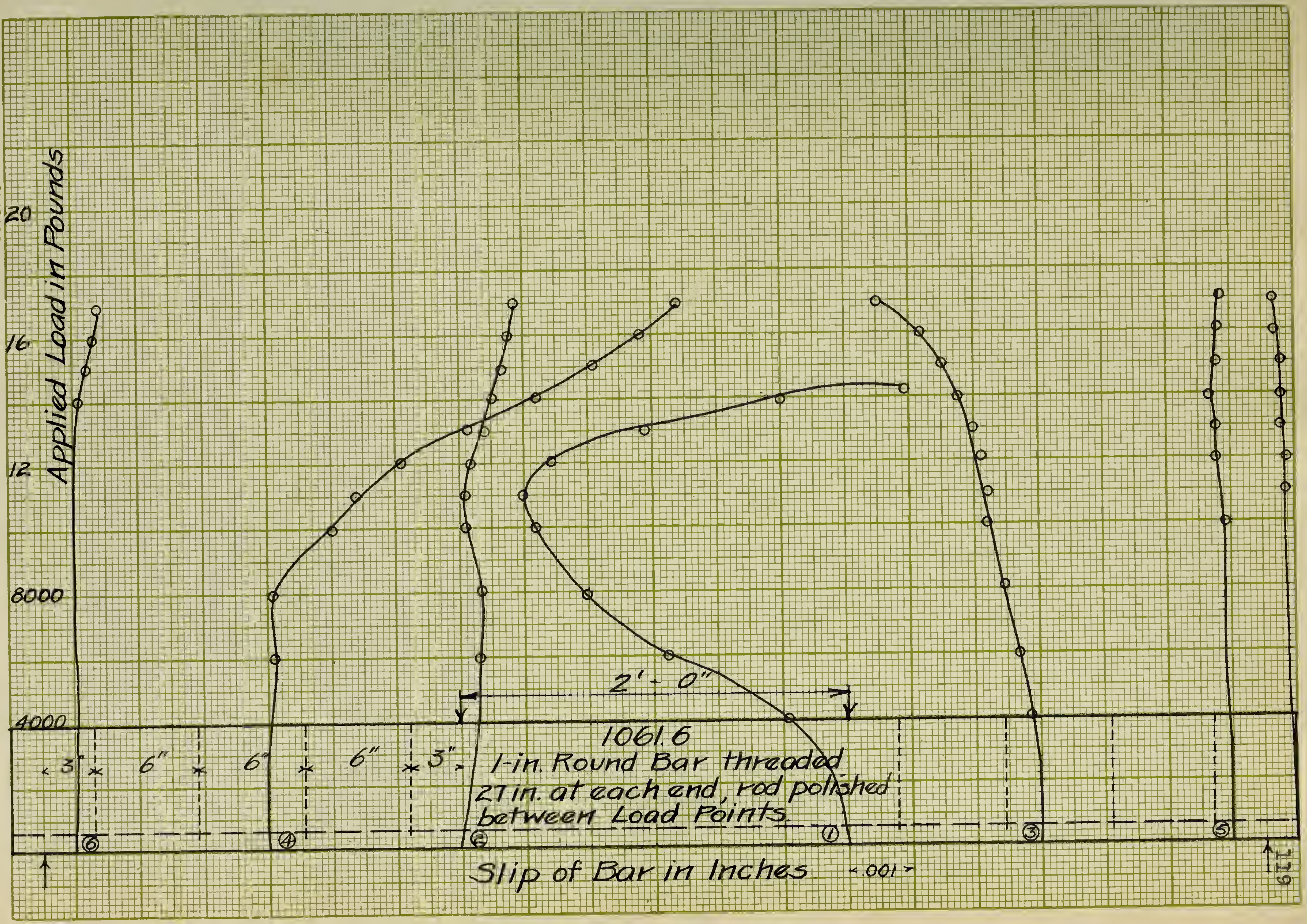


Applied Load in Inches
20
16
12
8000
4000
7"
6"
6"
6"
4"
2'-0"
1047.3
1-in. Square Twisted
Bar - 1 Twist per Foot
Slip of Bar in Inches
.001

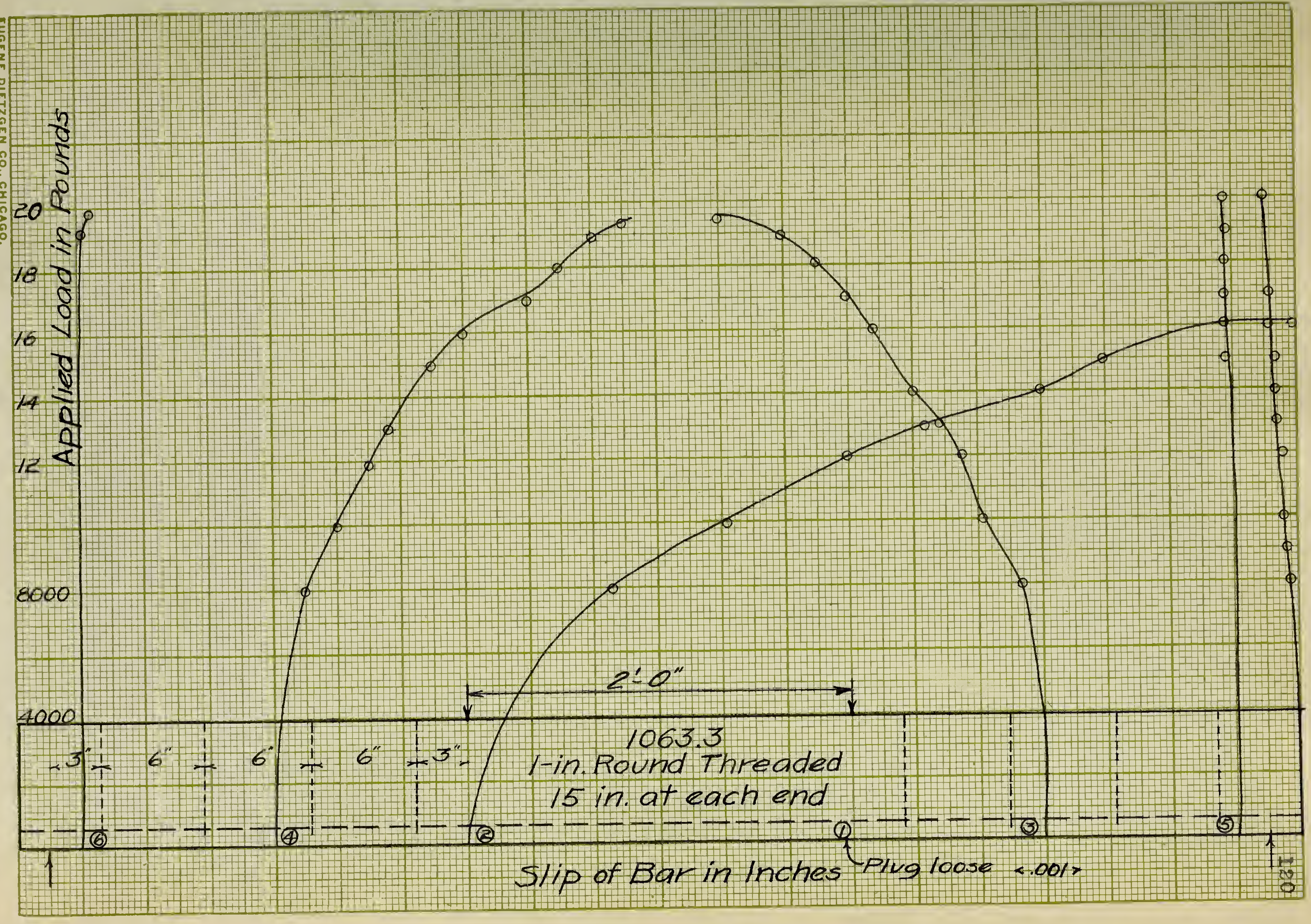


Applied Load in Pounds
24
20
16
12
8000
4000
3"
6"
6"
6"
3"
2'-0"
1048.3
1⅛-in. Corr. Round Bar
6
4
2
3
5
7
Slip of Bar in Inches
.001
117
EUGENE DIETZGEN CO., CHICAGO.

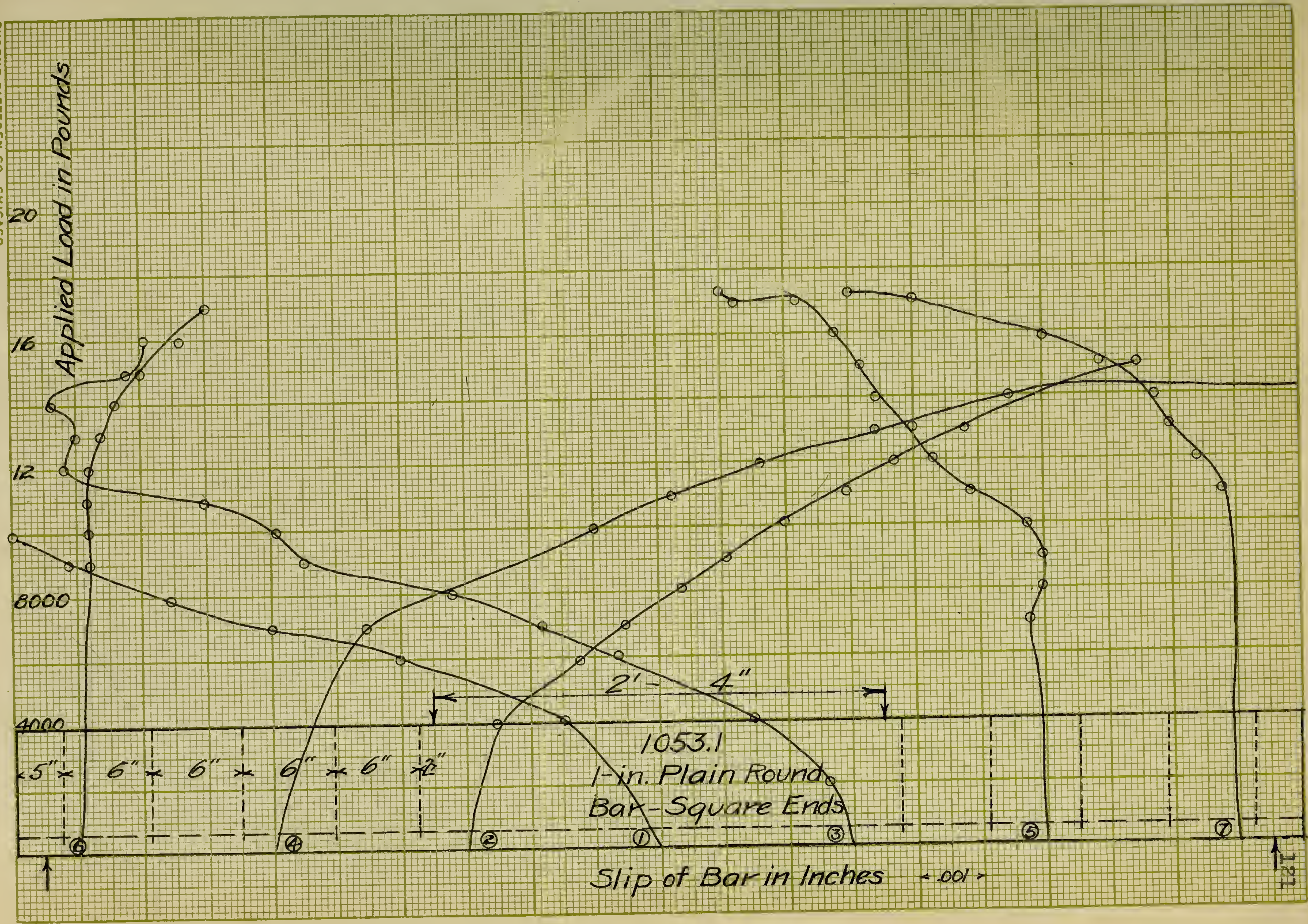

Applied Load in Pounds
24
20
16
12
8000
4000
2'-0"
1048.4
$1\frac{1}{8}$ in. Corr. Round Bar
3"
6"
6"
6"
3"
Slip in Inches
.001
118



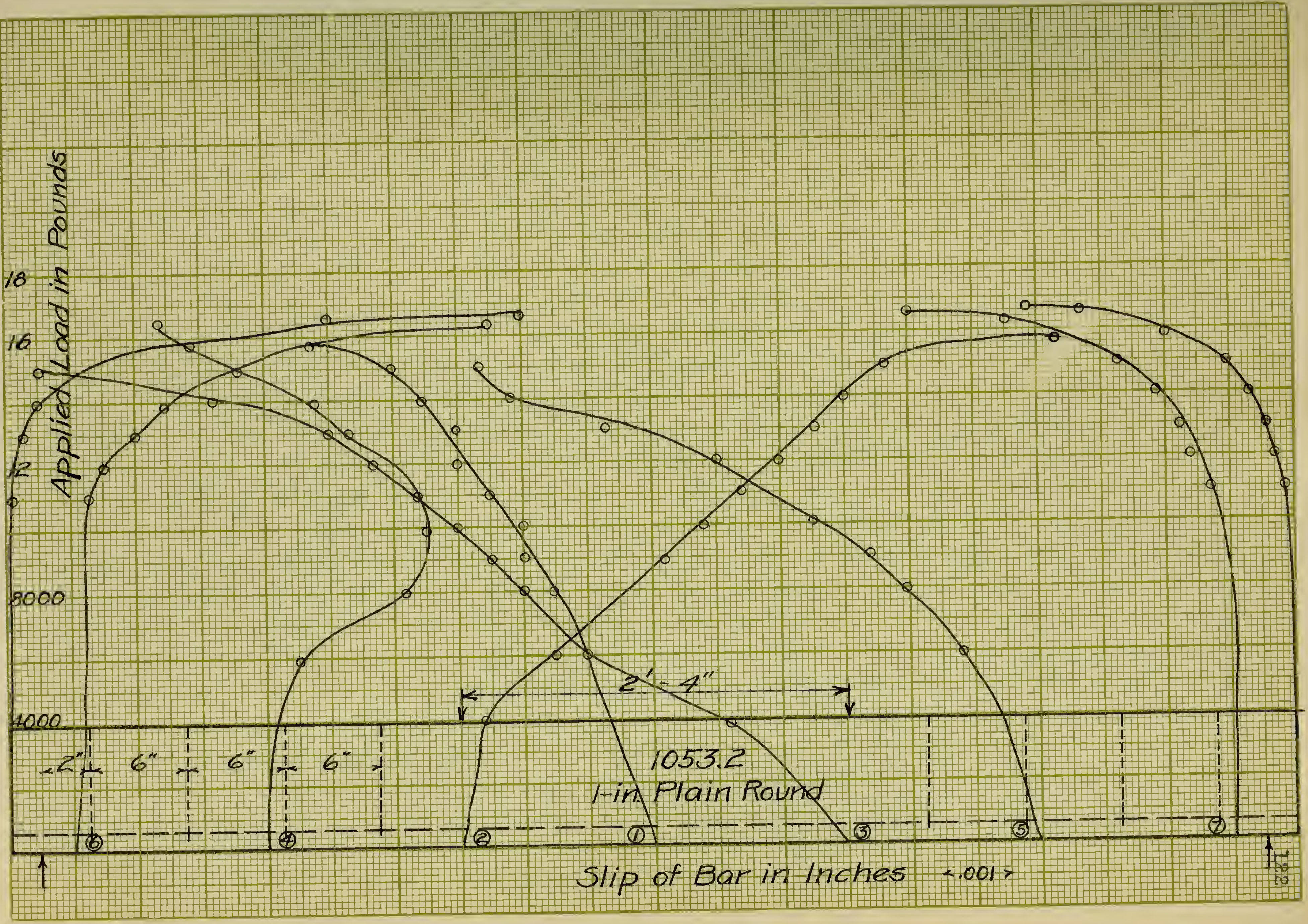
EUGENE DIETZGEN CO., CHICAGO.

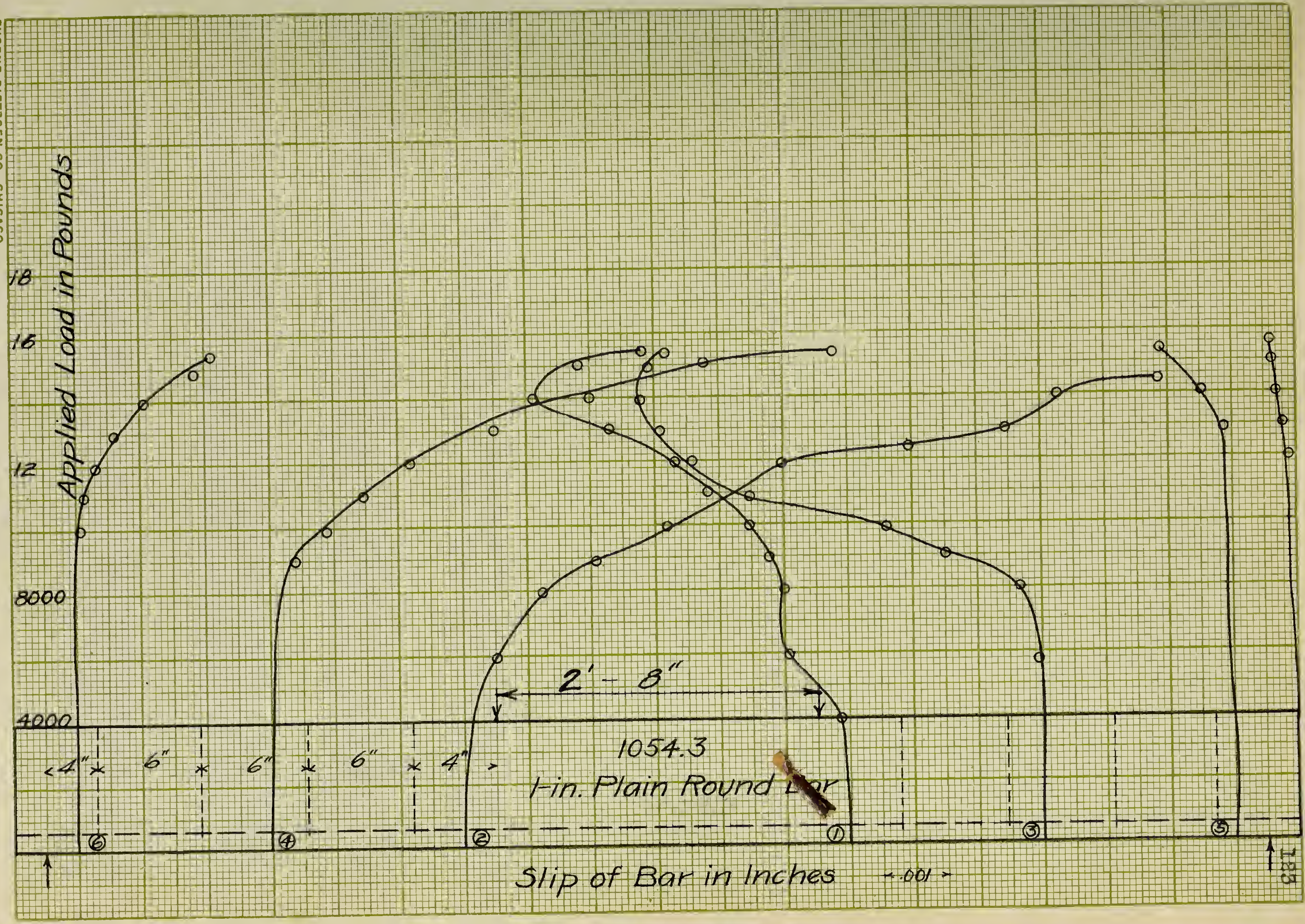


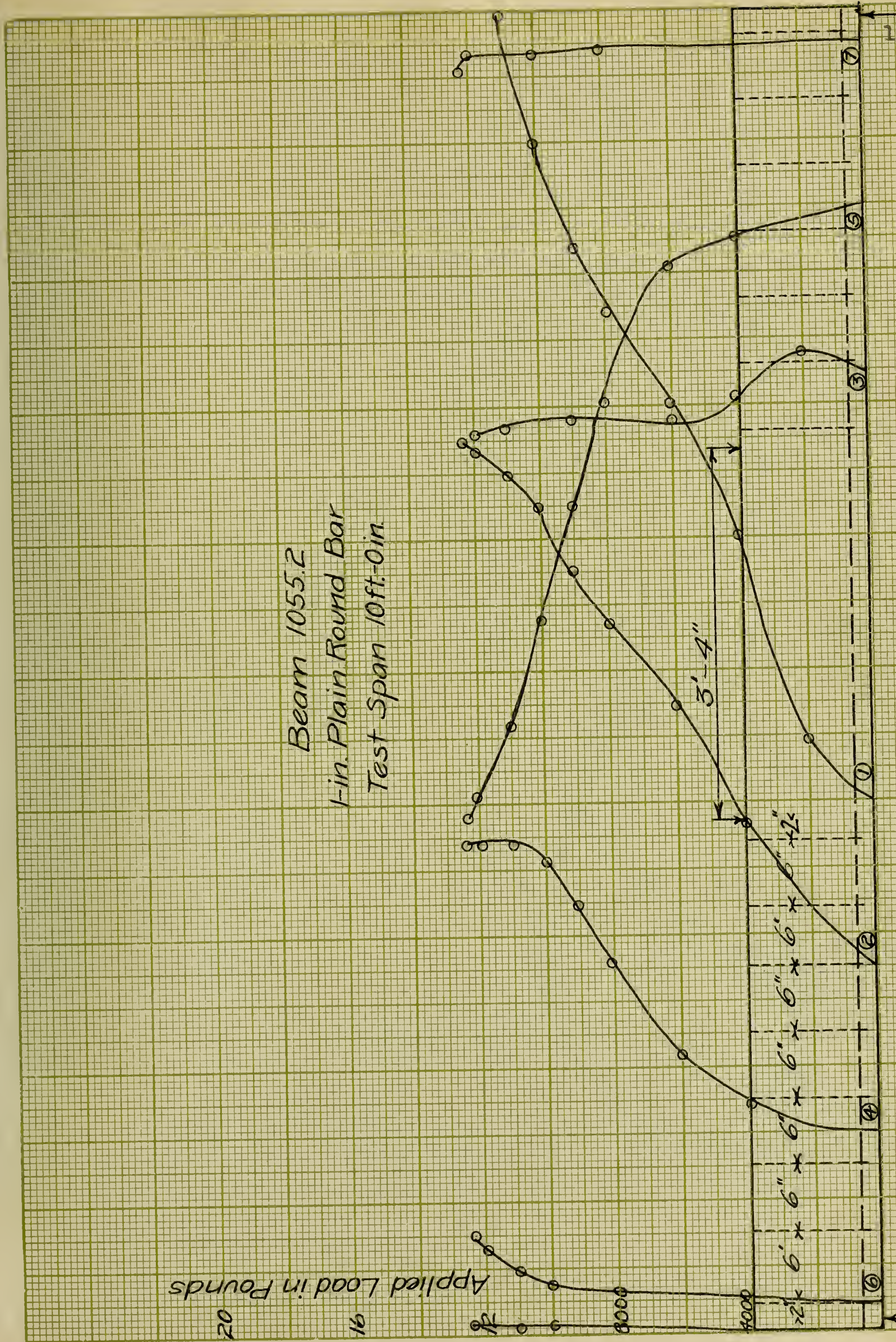
Applied Load in Pounds
20
18
16
14
12
8000
4000
2'-0"
1063.3
1-in. Round Threaded
15 in. at each end
3"
6"
6"
6"
3"
6
4
2
1
3
5
Slip of Bar in Inches
Plug loose
.001
120
EUGENE DIETZGEN CO., CHICAGO.

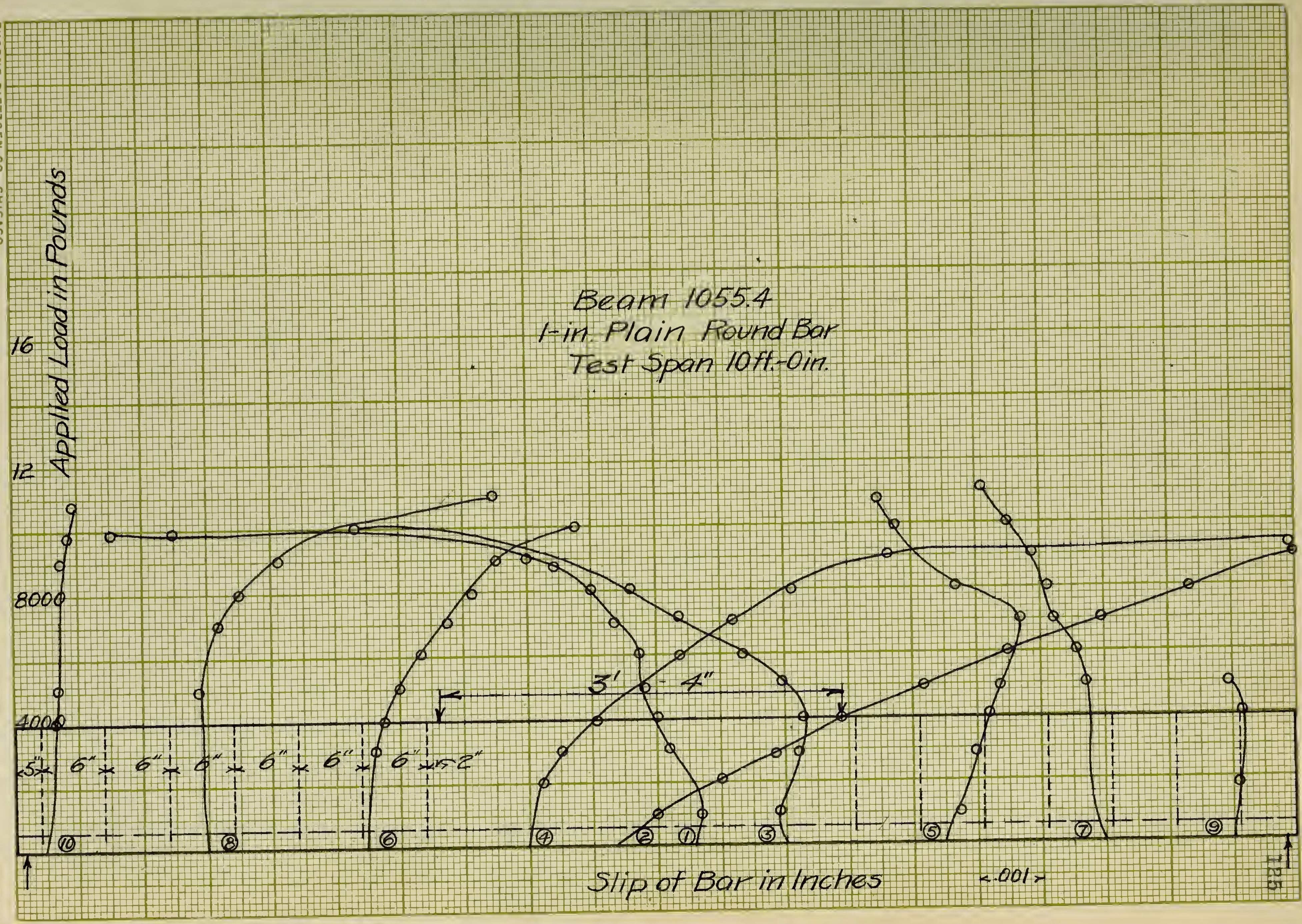


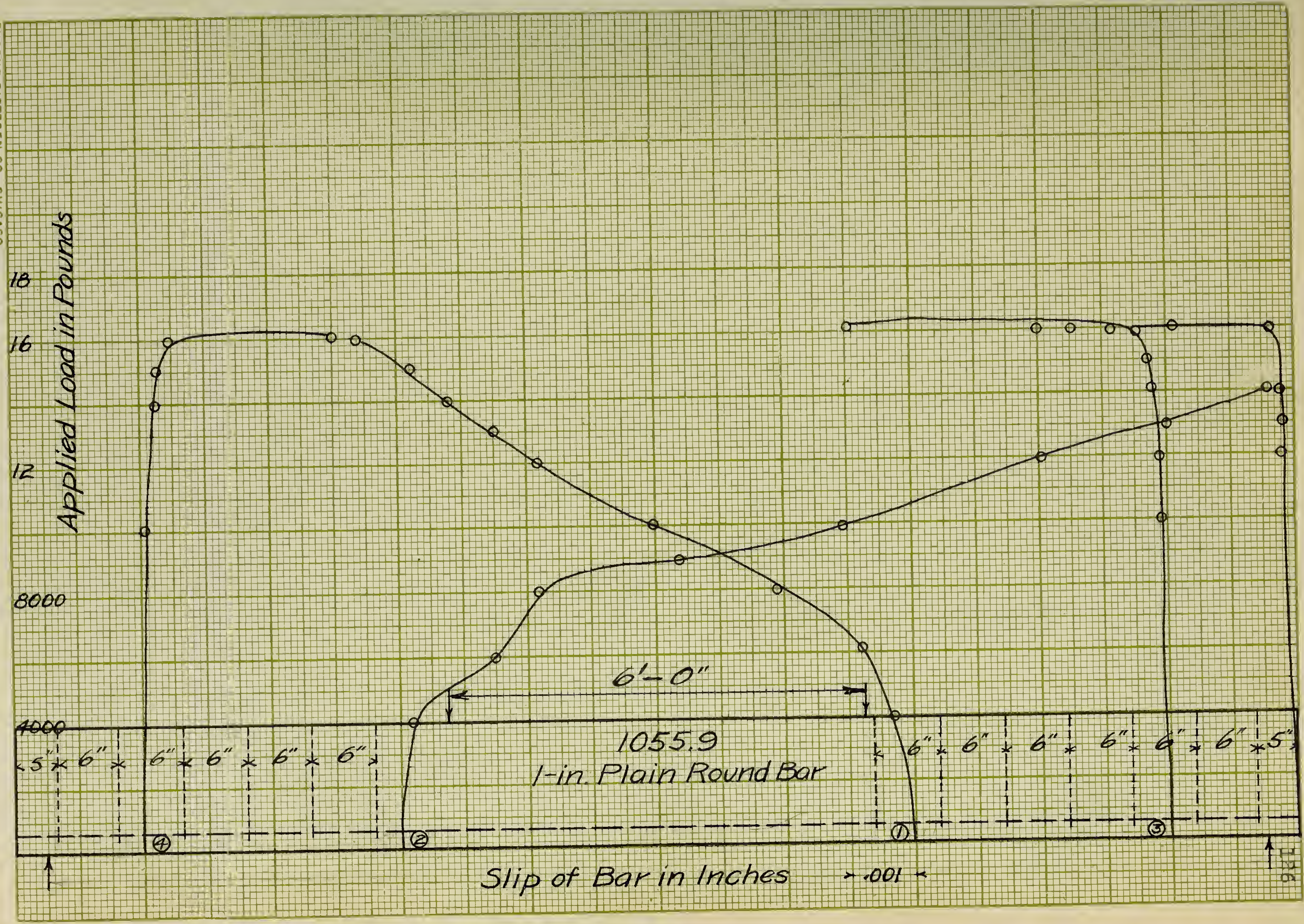
Applied Load in Pounds
20
16
12
8000
4000
2'- 4"
1053.1
1-in. Plain Round
Bar-Square Ends
5" 6" 6" 6" 6" 2"
Slip of Bar in Inches
.001
121


Applied Load in Pounds
18
16
12
8000
4000
2'-4"
1053.2
1-in. Plain Round
2"
6"
6"
6"
6
4
2
1
3
5
7
Slip of Bar in Inches
.001
122

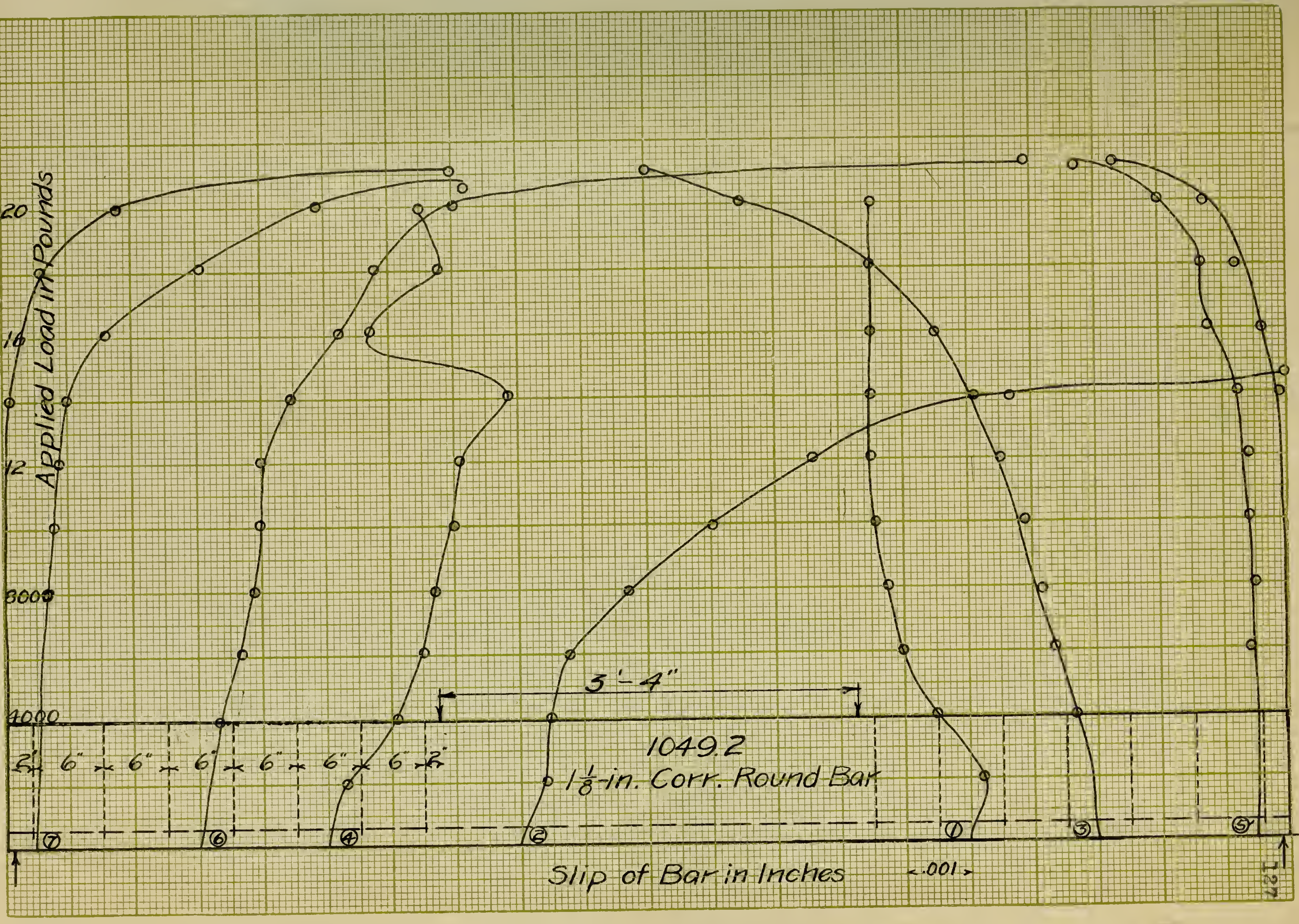

Applied Load in Pounds
18
16
12
8000
4000
4"
6"
6"
6"
4"
2' - 8"
1054.3
1-in. Plain Round
1
2
3
4
5
6
Slip of Bar in Inches
.001
EUGENE DIETZGEN CO., CHICAGO.


Beam 1055.2
1-in. Plain Round Bar
Test Span 10ft.-0in.
Slip of Bar in Inches
<.001>
Applied Load in Pounds
3'-4"
20
16
12
8000
4000


Beam 1055.4
1-in. Plain Round Bar
Test Span 10ft.-0in.
Applied Load in Pounds
16
12
8000
4000
3' - 4"
5" 6" 6" 6" 6" 6" 6" 2"
10
8
6
4
2
1
3
5
7
9
Slip of Bar in Inches
.001



EUGENE DIETZGEN CO., CHICAGO.


Applied Load in Pounds
20
16
12
8000
4000
3'-4"
1049.2
$1\frac{1}{8}$-in. Corr. Round Bar
2" 6" 6" 6" 6" 6" 6" 2"
7
6
4
2
1
3
5
Slip of Bar in Inches
.001